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Freese et al.

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(54) **METHODS AND DEVICES FOR OPTICALLY DETERMINING A CHARACTERISTIC OF A SUBSTANCE**

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Related U.S. Application Data

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(51) **Int. Cl.**

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G01N 21/17	(2006.01)
G01J 3/02	(2006.01)
G01J 3/28	(2006.01)
G01N 21/27	(2006.01)
G01N 21/31	(2006.01)
G06E 3/00	(2006.01)
G01J 3/12	(2006.01)

(52) **U.S. Cl.**

CPC ***G01N 21/17*** (2013.01); ***G01J 3/0294*** (2013.01); ***G01J 3/28*** (2013.01); ***G01N 21/274*** (2013.01); ***G01N 21/31*** (2013.01); ***G06E 3/001*** (2013.01); *G01J 2003/1226* (2013.01); *G01N 2021/3137* (2013.01); *G01N 2021/3174* (2013.01)

(58) **Field of Classification Search**

USPC 356/432–448; 250/253–266, 269, 234

See application file for complete search history.

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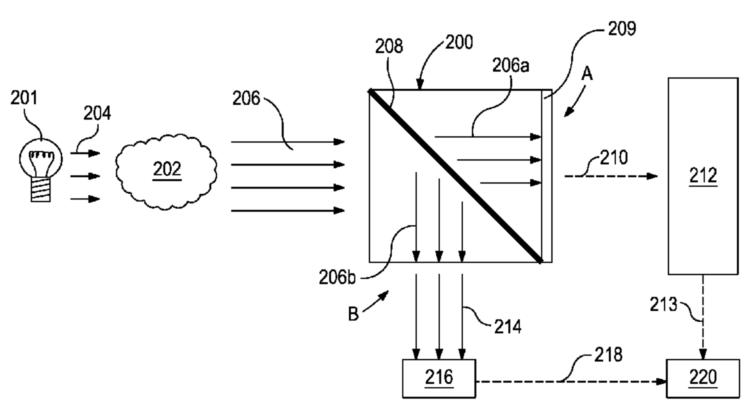
(57) **ABSTRACT**

Using an optical computing device includes optically interacting electromagnetic radiation with a sample and a first integrated computational element arranged within a primary channel, optically interacting the electromagnetic radiation with the sample and a second integrated computational element arranged within a reference channel, producing first and second modified electromagnetic radiations from the first and second integrated computational elements, respectively, receiving the first modified electromagnetic radiation with a first detector, and receiving the second modified electromagnetic radiation with a second detector, generating a first output signal with the first detector and a second output signal with the second detector, and computationally combining the first and second output signals with a signal processor to determine the characteristic of interest of the sample.

20 Claims, 6 Drawing Sheets



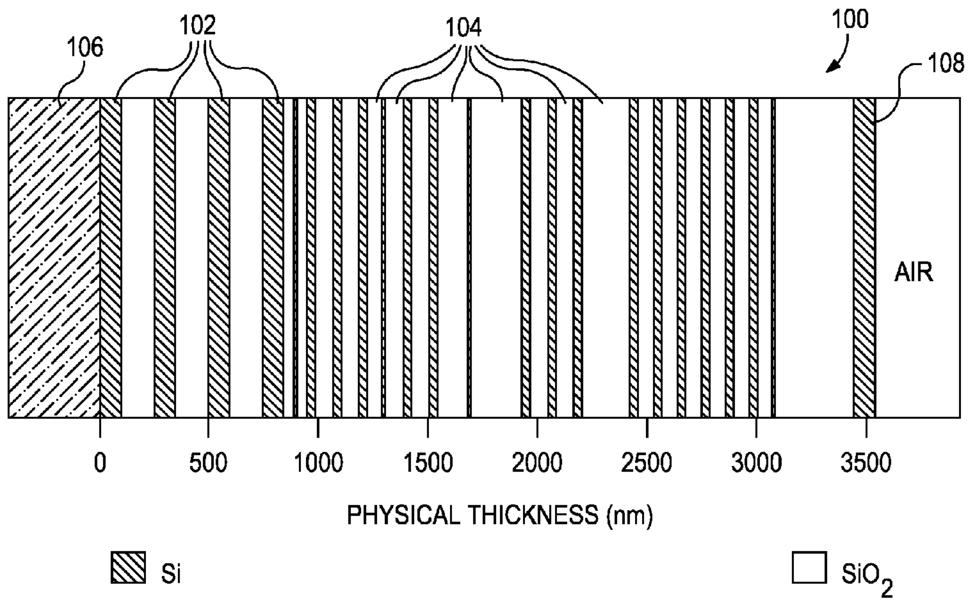

106
102
104
100
108
AIR
0
500
1000
1500
2000
2500
3000
3500
PHYSICAL THICKNESS (nm)
Si
SiO_2

FIG. 1

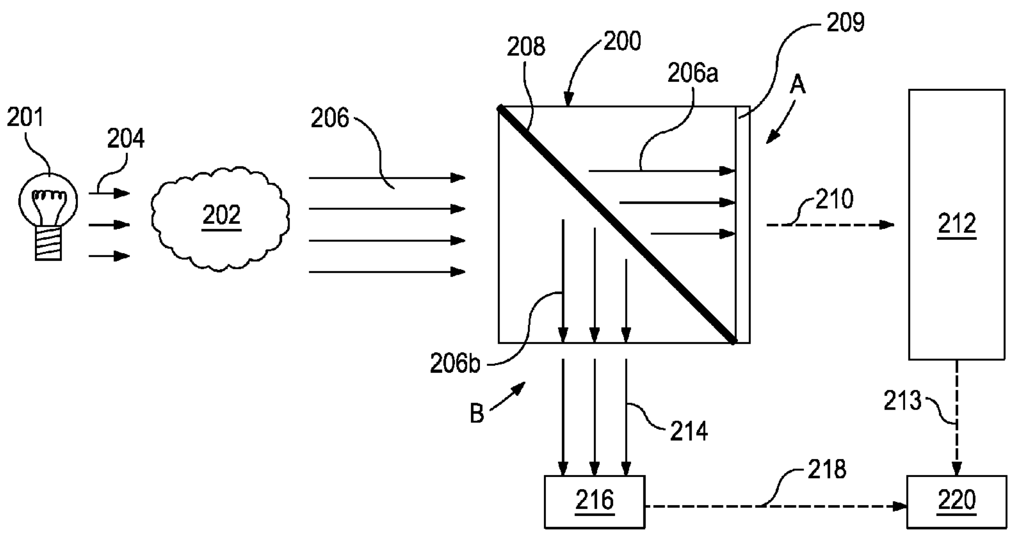
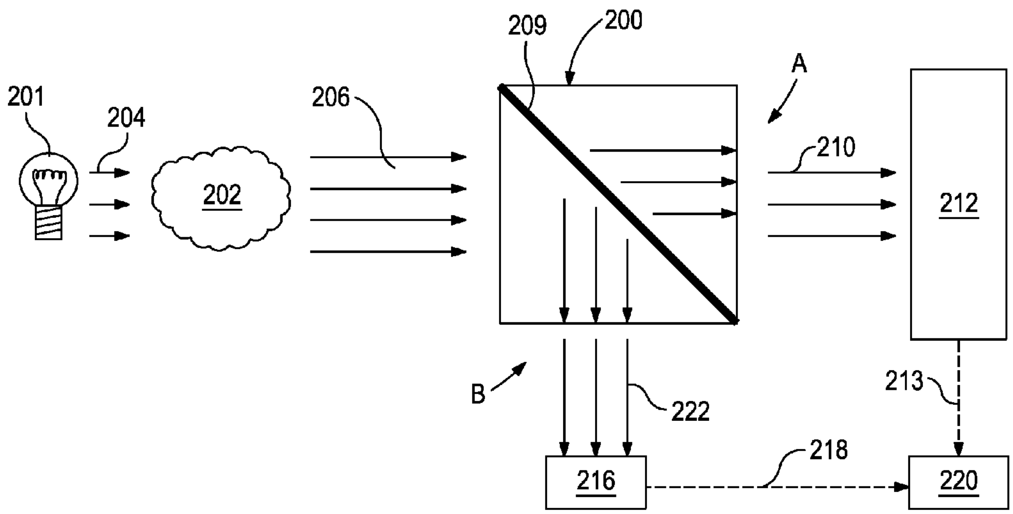
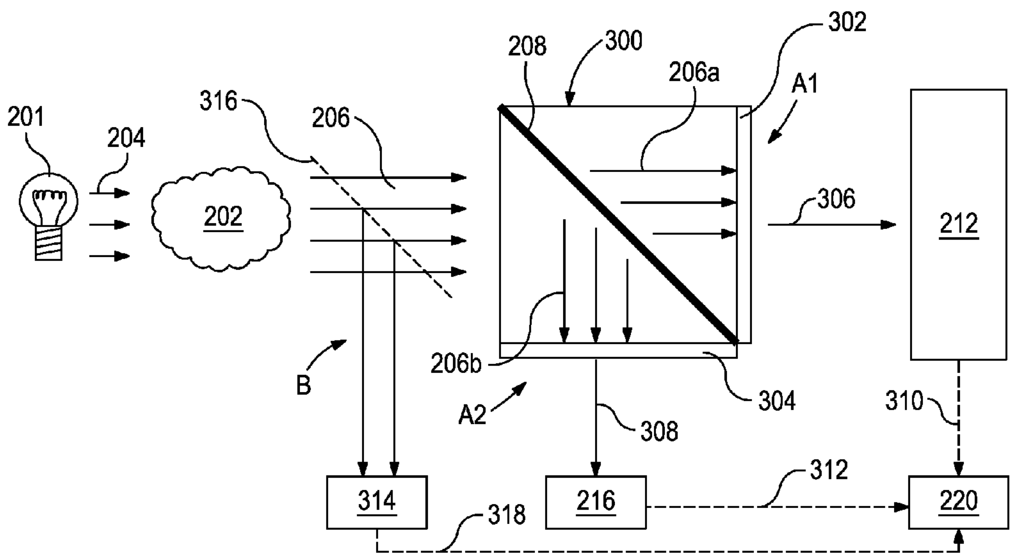

201
204
202
206
208
200
206a
209
A
210
212
206b
B
214
213
216
218
220

FIG. 2a



209
200
A
201
204
206
210
202
212
B
222
213
216
218
220

FIG. 2b



302
208
300
206a
A1
201
316
206
204
202
306
212
206b
B
A2
304
308
310
312
314
216
220
318

FIG. 3a

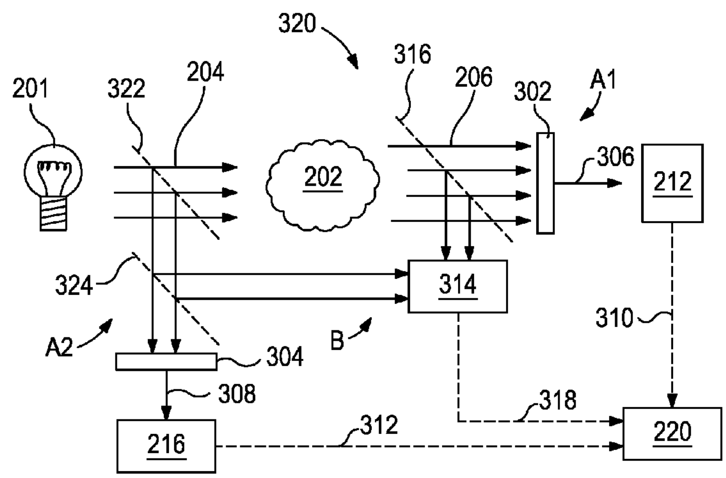

320
201
322
204
316
206
302
A1
306
202
212
324
314
310
A2
B
304
308
318
312
216
220

FIG. 3b

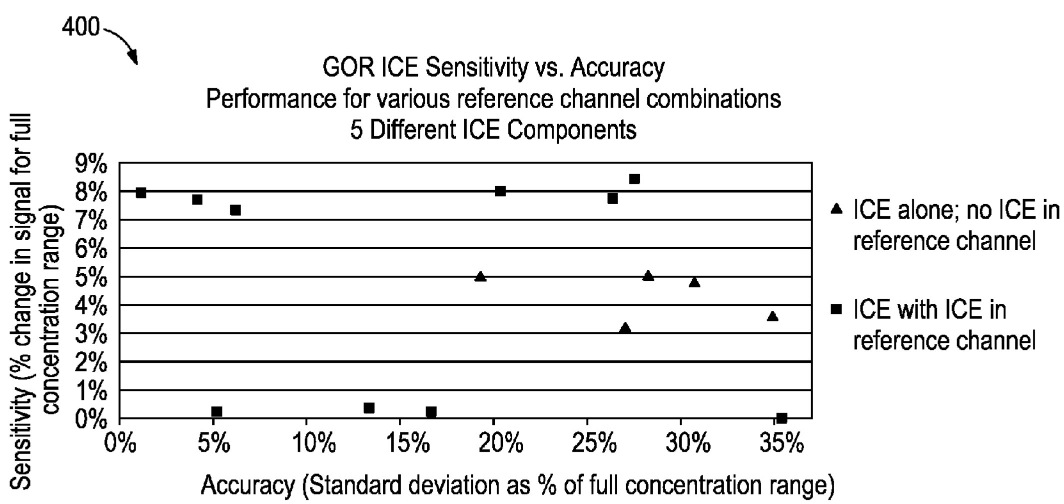
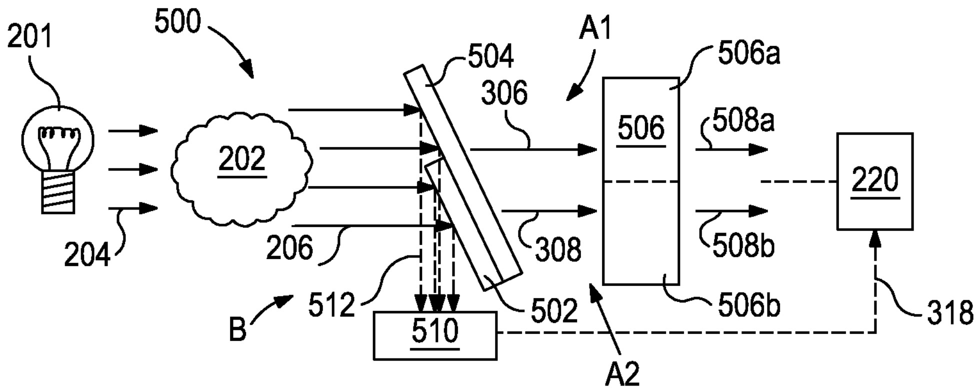
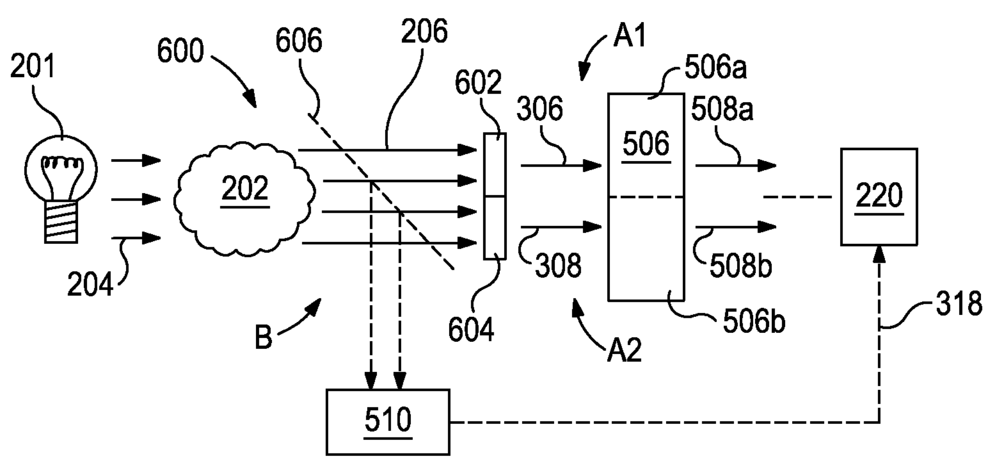

400
GOR ICE Sensitivity vs. Accuracy
Performance for various reference channel combinations
5 Different ICE Components
Sensitivity (% change in signal for full concentration range)
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0%
5%
10%
15%
20%
25%
30%
35%
Accuracy (Standard deviation as % of full concentration range)
ICE alone; no ICE in reference channel
ICE with ICE in reference channel

FIG. 4



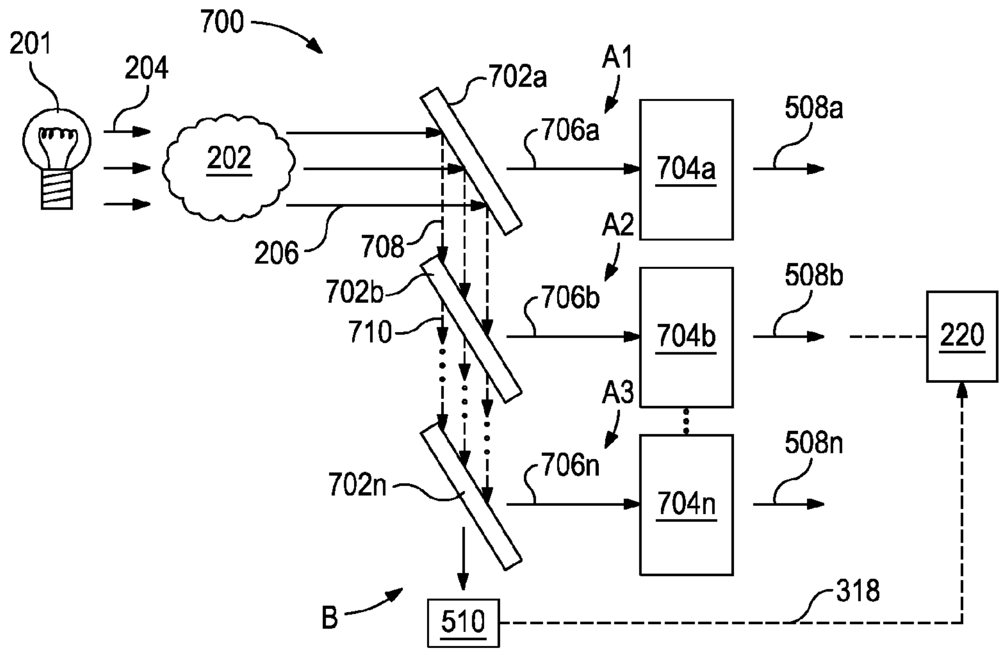
201
500
504
A1
506a
306
506
508a
202
220
204
206
308
508b
512
502
506b
318
B
510
A2

FIG. 5



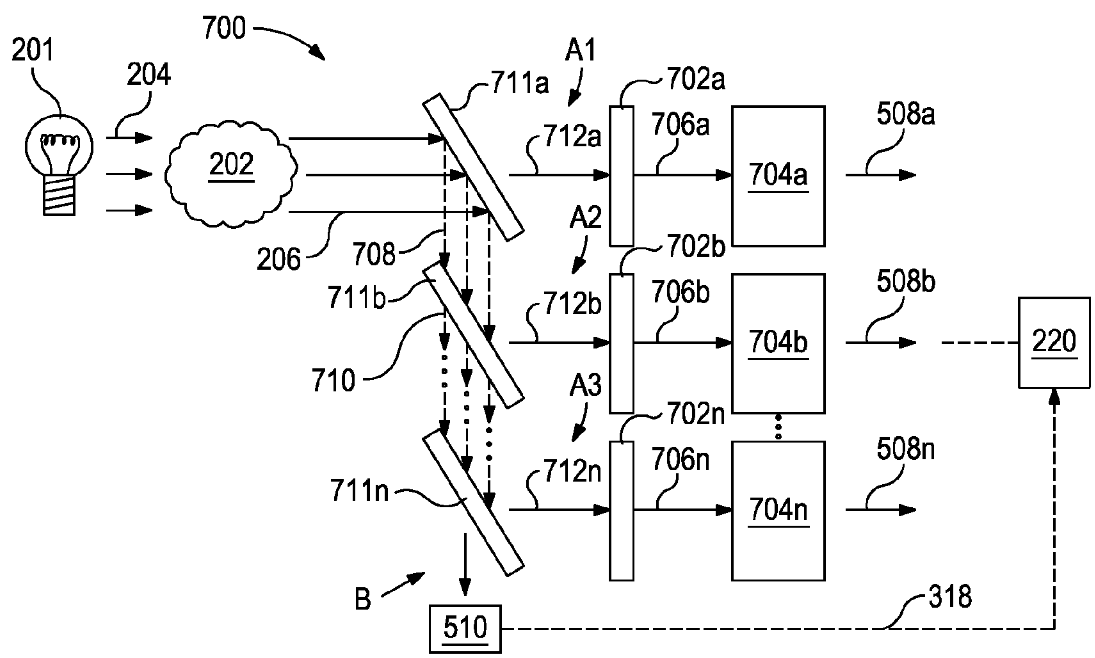
201
600
606
206
A1
602
506a
306
508a
506
202
220
204
308
508b
604
506b
318
B
A2
510

FIG. 6



700
201
204
202
206
702a
A1
706a
704a
508a
708
A2
702b
706b
704b
508b
220
710
A3
702n
706n
704n
508n
B
510
318

FIG. 7



700
201
204
202
206
711a
A1
712a
702a
706a
704a
508a
708
A2
711b
712b
702b
706b
704b
508b
220
710
A3
711n
712n
702n
706n
704n
508n
B
510
318

FIG. 8

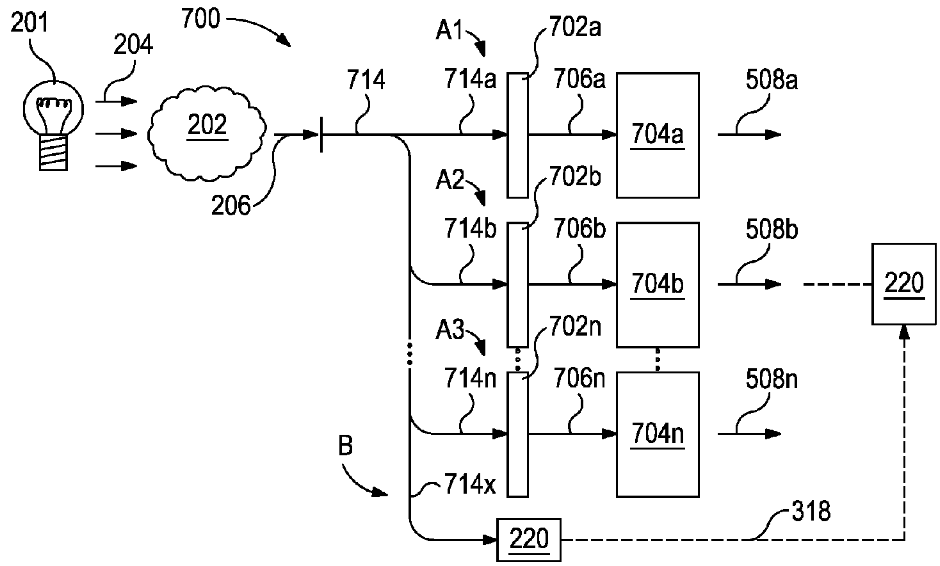


FIG. 9

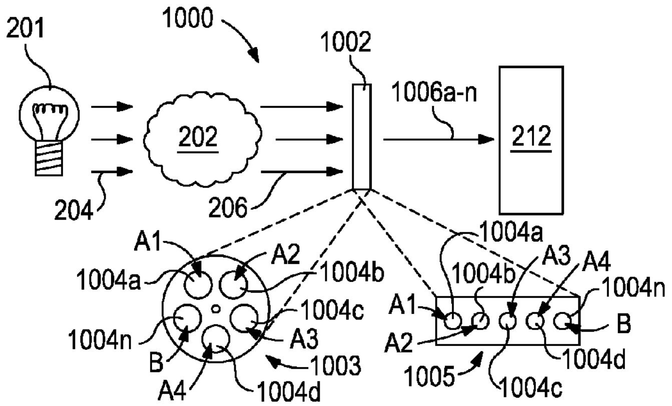


FIG. 10

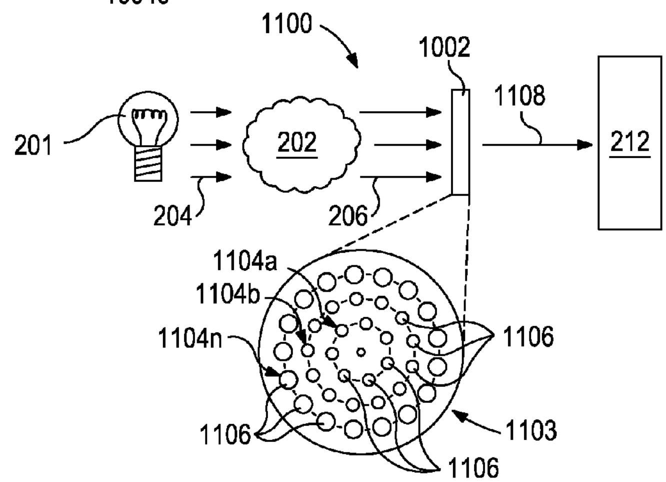


FIG. 11

METHODS AND DEVICES FOR OPTICALLY DETERMINING A CHARACTERISTIC OF A SUBSTANCE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a divisional application of and claiming priority to U.S. patent application Ser. No. 13/456,379, filed on Apr. 16, 2012.

BACKGROUND

The present invention generally relates to systems and methods of optical computing and, more specifically, to systems and methods of determining a particular characteristic of a substance using two or more integrated computational elements.

Spectroscopic techniques for measuring various characteristics of materials are well known and are routinely used under laboratory conditions. In some cases, these spectroscopic techniques can be carried out without using an involved sample preparation. It is more common, however, to carry out various sample preparation steps before conducting the analysis. Reasons for conducting sample preparation steps can include, for example, removing interfering background materials from the analyte of interest, converting the analyte of interest into a chemical form that can be better detected by the chosen spectroscopic technique, and adding standards to improve the accuracy of quantitative measurements. Thus, there is usually a delay in obtaining an analysis due to sample preparation time, even discounting the transit time of transporting the sample to a laboratory.

Although spectroscopic techniques can, at least in principle, be conducted at a job site or in a process, the foregoing concerns regarding sample preparation times can still apply. Furthermore, the transitioning of spectroscopic instruments from a laboratory into a field or process environment can be expensive and complex. Reasons for these issues can include, for example, the need to overcome inconsistent temperature, humidity, and vibration encountered during field or process use. Furthermore, sample preparation, when required, can be difficult under field analysis conditions. The difficulty of performing sample preparation in the field can be especially problematic in the presence of interfering materials, which can further complicate conventional spectroscopic analyses. Quantitative spectroscopic measurements can be particularly challenging in both field and laboratory settings due to the need for precision and accuracy in sample preparation and spectral interpretation.

SUMMARY OF THE INVENTION

The present invention generally relates to systems and methods of optical computing and, more specifically, to systems and methods of determining a particular characteristic of a substance using two or more integrated computational elements.

In some embodiments of the disclosure, a device is disclosed that may include an electromagnetic radiation source configured to optically interact with a sample having a characteristic of interest, and a first integrated computational element arranged within a primary channel and configured to optically interact with the electromagnetic radiation source and produce a first modified electromagnetic radiation. The device may also include a second integrated computational element arranged within a reference channel and configured

to optically interact with the electromagnetic radiation source and produce a second modified electromagnetic radiation, and a first detector arranged to receive the first and second modified electromagnetic radiations from the first and second integrated computational elements, respectively, and generate an output signal corresponding to the characteristic of the sample.

In some embodiments of the disclosure, a method of determining a characteristic of a sample is disclosed. The method may include optically interacting an electromagnetic radiation source with the sample and a first integrated computational element arranged within a primary channel and a second integrated computational element arranged within a reference channel. The method may also include producing first and second modified electromagnetic radiations from the first and second integrated computational elements, respectively, and receiving the first and second modified electromagnetic radiations with a first detector. The method may further include generating an output signal with the first detector, the output signal corresponding to the characteristic of the sample.

In some embodiments of the disclosure, another device is disclosed and may include an electromagnetic radiation source configured to optically interact with a sample having a characteristic of interest, and a first integrated computational element arranged within a primary channel and configured to optically interact with the electromagnetic radiation source and produce a first modified electromagnetic radiation. The device may also include a second integrated computational element arranged within a second channel and configured to optically interact with the electromagnetic radiation source and produce a second modified electromagnetic radiation, and a first detector arranged to receive the first modified electromagnetic radiation and generate a first output signal. The device may further include a second detector arranged to receive the second modified electromagnetic radiation and generate a second output signal, and a signal processor configured to receive and computationally combine the first and second output signals to determine the characteristic of interest of the sample.

In some embodiments of the disclosure, another method of determining a characteristic of a sample is disclosed. The method may include optically interacting an electromagnetic radiation source with the sample and a first integrated computational element arranged within a primary channel and a second integrated computational element arranged within a reference channel, and producing first and second modified electromagnetic radiations from the first and second integrated computational elements, respectively. The method may also include receiving the first modified electromagnetic radiation with a first detector, and receiving the second modified electromagnetic radiation with a second detector. The method may further include generating a first output signal with the first detector and a second output signal with the second detector, and computationally combining the first and second output with a signal processor to determine the characteristic of interest of the sample.

The features and advantages of the present invention will be readily apparent to one having ordinary skill in the art upon a reading of the description of the preferred embodiments that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

The following figures are included to illustrate certain aspects of the present invention, and should not be viewed as exclusive embodiments. The subject matter disclosed is capable of considerable modification, alteration, and equivalents in form and function, as will occur to one having ordinary skill in the art and having the benefit of this disclosure.

FIG. **1** illustrates an exemplary integrated computation element, according to one or more embodiments.

FIG. **2***a* illustrates a block diagram non-mechanistically illustrating how an optical computing device distinguishes electromagnetic radiation related to a characteristic of interest from other electromagnetic radiation, according to one or more embodiments.

FIG. **2***b* illustrates another block diagram non-mechanistically illustrating how an optical computing device distinguishes electromagnetic radiation related to a characteristic of interest from other electromagnetic radiation, according to one or more embodiments.

FIG. **3***a* illustrates an exemplary optical computing device, according to one or more embodiments.

FIG. **3***b* illustrates another exemplary optical computing device, according to one or more embodiments.

FIG. **4** illustrates a graph indicating the advantages of arranging integrated computational elements in both the primary and reference channels, according to one or more embodiments.

FIG. **5** illustrates another exemplary optical computing device, according to one or more embodiments.

FIG. **6** illustrates another exemplary optical computing device, according to one or more embodiments.

FIG. **7** illustrates another exemplary optical computing device, according to one or more embodiments.

FIGS. **8** and **9** illustrate variations of the optical computing device of FIG. **7**, according to one or more embodiments.

FIG. **10** illustrates another exemplary optical computing device, according to one or more embodiments.

FIG. **11** illustrates another exemplary optical computing device, according to one or more embodiments.

DETAILED DESCRIPTION

The present invention generally relates to systems and methods of optical computing and, more specifically, to systems and methods of determining a particular characteristic of a substance using two or more integrated computational elements.

Embodiments described herein include various configurations of optical computing devices, also commonly referred to as opticoanalytical devices. The various embodiments of the disclosed optical computing devices may be suitable for use in the oil and gas industry. For example, embodiments disclosed herein provide systems and/or devices capable of providing a relatively low cost, rugged, and accurate system for monitoring petroleum quality for the purpose of optimizing decision making at a well site and efficient management of hydrocarbon production. Embodiments disclosed herein may also be useful in determining concentrations of various analytes of interest in hydrocarbons present within a wellbore. Embodiments disclosed herein may also be useful in determining concentrations of various analytes of interest in other fluids, such as water, important in the oil and gas industry. It will be appreciated, however, that the various disclosed systems and devices are equally applicable to other technology fields including, but not limited to, the food and drug industry, industrial applications, mining industries, or any field where it may be advantageous to determine in real-time the concentrations of a specific character or analyte of interest of a compound or material.

As used herein, the term "fluid" refers to any substance that is capable of flowing, including particulate solids, liquids, gases, slurries, emulsions, powders, muds, glasses, combinations thereof, and the like. In some embodiments, the fluid can be an aqueous fluid, including water or the like. In some embodiments, the fluid can be a non-aqueous fluid, including organic compounds, more specifically, hydrocarbons, oil, a refined component of oil, petrochemical products, and the like. In some embodiments, the fluid can be a treatment fluid or a formation fluid. Fluids can include various flowable mixtures of solids, liquid and/or gases. Illustrative gases that can be considered fluids according to the present embodiments include, for example, air, nitrogen, carbon dioxide, argon, helium, hydrogen disulfide, mercaptan, thiophene, methane, ethane, butane, and other hydrocarbon gases, and/or the like.

As used herein, the term "characteristic" refers to a chemical, mechanical, or physical property of a substance. A characteristic of a substance may include a quantitative value of one or more chemical components therein. Such chemical components may be referred to as "analytes." Illustrative characteristics of a substance that can be monitored with the optical computing devices disclosed herein can include, for example, chemical composition (identity and concentration, in total or of individual components), impurity content, pH, viscosity, density, ionic strength, total dissolved solids, salt content, porosity, opacity, bacteria content, combinations thereof, and the like.

As used herein, the term "electromagnetic radiation" refers to radio waves, microwave radiation, infrared and near-infrared radiation, visible light, ultraviolet light, X-ray radiation and gamma ray radiation.

As used herein, the term "optical computing device" refers to an optical device that is configured to receive an input of electromagnetic radiation from a substance or sample of the substance and produce an output of electromagnetic radiation from a processing element. The processing element may be, for example, an integrated computational element. The electromagnetic radiation emanating from the processing element is changed in some way so as to be readable by a detector, such that an output of the detector can be correlated to at least one characteristic of the substance. The output of electromagnetic radiation from the processing element can be reflected electromagnetic radiation, transmitted electromagnetic radiation, and/or dispersed electromagnetic radiation. As will be appreciated by those skilled in the art, whether reflected or transmitted electromagnetic radiation is analyzed by the detector will be a matter of routine experimental design. In addition, emission and/or scattering of the substance, for example via fluorescence, luminescence, radiation and re-radiation, Raman scattering, and/or Raleigh scattering can also be monitored by the optical computing devices.

As used herein, the term "optically interact" or variations thereof refers to the reflection, transmission, scattering, diffraction, radiating, re-radiating, or absorption of electromagnetic radiation either on, through, or from one or more processing elements, such as integrated computational elements. Accordingly, optically interacted light refers to light that has been reflected, transmitted, scattered, diffracted, or absorbed by, emitted, radiated, or re-radiated, for example, using the integrated computational elements, but may also apply to interaction with a sample substance.

As used herein, the term "sample," or variations thereof, refers to at least a portion of a substance of interest to be tested or otherwise evaluated using the optical computing devices described herein. The sample includes the characteristic of interest, as defined above, and may be any fluid, as defined herein, or otherwise any solid substance or material such as, but not limited to, rock formations, concrete, other solid surfaces, etc.

At the very least, the exemplary optical computing devices disclosed herein will each include an electromagnetic radiation source, at least two processing elements (e.g., integrated computational elements), and at least one detector arranged to receive optically interacted light from the at least two processing elements. As disclosed below, however, in one or more embodiments, the electromagnetic radiation source may be omitted and instead the electromagnetic radiation may be derived from the substance itself or a sample of the substance. In some embodiments, the exemplary optical computing devices may be specifically configured for detecting, analyzing, and quantitatively measuring a particular characteristic or analyte of interest of a given sample or substance. In other embodiments, the exemplary optical computing devices may be general purpose optical devices, with post-acquisition processing (e.g., through computer means) being used to specifically detect the characteristic of the sample.

In some embodiments, suitable structural components for the exemplary optical computing devices disclosed herein are described in commonly owned U.S. Pat. Nos. 6,198,531; 6,529,276; 7,123,844; 7,834,999; 7,711,605, 7,920,258, and 8,049,881, and U.S. patent application Ser. No. 12/094,460 (U.S. Pat. App. Pub. No. 2009/0219538); and Ser. No. 12/094,465 (U.S. Pat. App. Pub. No. 2009/0219539). As will be appreciated, variations of the structural components of the optical computing devices described in the above-referenced patents and patent applications may be suitable, without departing from the scope of the disclosure, and therefore should not be considered limiting to the various embodiments disclosed herein.

The optical computing devices described in the foregoing patents and patent applications combine the advantage of the power, precision and accuracy associated with laboratory spectrometers, while being extremely rugged and suitable for field use. Furthermore, the optical computing devices can perform calculations (analyses) in real-time or near real-time without the need for sample processing. In this regard, the optical computing devices can be specifically configured to detect and analyze particular characteristics and/or analytes of interest. As a result, interfering signals are discriminated from those of interest in a sample by appropriate configuration of the optical computing devices, such that the optical computing devices provide a rapid response regarding the characteristics of the sample as based on the detected output. In some embodiments, the detected output can be converted into a voltage that is distinctive of the magnitude of the characteristic being monitored in the sample. The foregoing advantages and others make the optical computing devices, and their variations generally described below, particularly well suited for field and downhole use.

The exemplary optical computing devices described herein can be configured to detect not only the composition and concentrations of a material or mixture of materials, but they also can be configured to determine physical properties and other characteristics of the material as well, based on their analysis of the electromagnetic radiation received from the sample. For example, the optical computing devices can be configured to determine the concentration of an analyte and correlate the determined concentration to a characteristic of a substance by using suitable processing means. As will be appreciated, the optical computing devices may be configured to detect as many characteristics or analytes as desired in a given sample. All that is required to accomplish the monitoring of multiple characteristics or analytes is the incorporation of suitable processing and detection means within the optical computing device for each characteristic or analyte. In some embodiments, the properties of a substance can be a combination of the properties of the analytes therein (e.g., a linear, non-linear, logarithmic, and/or exponential combination). Accordingly, the more characteristics and analytes that are detected and analyzed using the exemplary optical computing devices, the more accurately the properties of the given sample can be determined.

Fundamentally, optical computing devices utilize electromagnetic radiation to perform calculations, as opposed to the hardwired circuits of conventional electronic processors. When electromagnetic radiation interacts with a substance, unique physical and chemical information about the substance is encoded in the electromagnetic radiation that is reflected from, transmitted through, or radiated from the sample. This information is often referred to as the substance's spectral "fingerprint." The exemplary optical computing devices disclosed herein are capable of extracting the information of the spectral fingerprint of multiple characteristics or analytes within a substance and converting that information into a detectable output regarding the overall properties of a sample. That is, through suitable configurations of the exemplary optical computing devices, electromagnetic radiation associated with characteristics or analytes of interest in a substance can be distinguished from electromagnetic radiation associated with all other components of a sample in order to estimate the sample's properties in real-time or near real-time.

The processing elements used in the exemplary optical computing devices described herein may be characterized as integrated computational elements (ICE). The ICE are capable of distinguishing electromagnetic radiation related to the characteristic or analyte of interest from electromagnetic radiation related to other components of a sample substance. Referring to FIG. **1**, illustrated is an exemplary ICE **100** suitable for use in the various optical computing devices described herein, according to one or more embodiments. As illustrated, the ICE **100** may include a plurality of alternating layers **102** and **104**, such as silicon (Si) and SiO_2 (quartz), respectively. In general, these layers consist of materials whose index of refraction is high and low, respectively. Other examples might include niobia and niobium, germanium and germania, MgF, SiO, and other high and low index materials as known in the art. The layers **102**, **104** may be strategically deposited on an optical substrate **106**. In some embodiments, the optical substrate **106** is BK-7 optical glass. In other embodiments, the optical substrate **106** may be other types of optical substrates, such as quartz, sapphire, silicon, germanium, zinc selenide, zinc sulfide, or various plastics such as polycarbonate, polymethalmethacrylate (PMMA), polyvinylchloride (PVC), diamond, ceramics, etc., as known in the art.

At the opposite end (e.g., opposite the optical substrate **106**), the ICE **100** may include a layer **108** that is generally exposed to the environment of the device or installation. The number of layers **102**, **104** and the thickness of each layer **102**, **104** are determined from the spectral attributes acquired from a spectroscopic analysis of a characteristic of the sample substance using a conventional spectroscopic instrument. The spectrum of interest of a given characteristic of a sample typically includes any number of different wavelengths. It should be understood that the exemplary ICE **100** in FIG. **1** does not in fact represent any particular characteristic of a given sample, but is provided for purposes of illustration only. Consequently, the number of layers **102**, **104** and their relative thicknesses, as shown in FIG. **1**, bear no correlation to any particular characteristic of a given sample. Nor are the layers **102**, **104** and their relative thicknesses necessarily drawn to scale, and therefore should not be considered limiting of the present disclosure. Moreover, those skilled in the art will readily recognize that the materials that make up each layer **102**, **104** (i.e., Si and SiO_2) may vary, depending on the application, cost of materials, and/or applicability of the material to the sample substance. For example, the layers **102**, **104** may be made of, but are not limited to, silicon, germanium, water, combinations thereof, or other materials of interest.

In some embodiments, the material of each layer **102**, **104** can be doped or two or more materials can be combined in a manner to achieve the desired optical characteristic. In addition to solids, the exemplary ICE **100** may also contain liquids and/or gases, optionally in combination with solids, in order to produce a desired optical characteristic. In the case of gases and liquids, the ICE **100** can contain a corresponding vessel (not shown) which houses the gases or liquids. Exemplary variations of the ICE **100** may also include holographic optical elements, gratings, piezoelectric, light pipe, digital light pipe (DLP), and/or acousto-optic elements, for example, that can create transmission, reflection, and/or absorptive properties of interest.

The multiple layers **102**, **104** exhibit different refractive indices. By properly selecting the materials of the layers **102**, **104** and their relative spacing, the exemplary ICE **100** may be configured to selectively pass/reflect/refract predetermined fractions of light (i.e., electromagnetic radiation) at different wavelengths. Each wavelength is given a predetermined weighting or loading factor. The thicknesses and spacing of the layers **102**, **104** may be determined using a variety of approximation methods from the spectrograph of the character or analyte of interest. These methods may include inverse Fourier transform (IFT) of the optical transmission spectrum and structuring the ICE **100** as the physical representation of the IFT. The approximations convert the IFT into a structure based on known materials with constant refractive indices. Further information regarding the structures and design of exemplary integrated computational elements (also referred to as multivariate optical elements) is provided in *Applied Optics*, Vol. 35, pp. 5484-5492 (1996) and Vol. 129, pp. 2876-2893.

The weightings that the layers **102**, **104** of the ICE **100** apply at each wavelength are set to the regression weightings described with respect to a known equation, or data, or spectral signature. Briefly, the ICE **100** may be configured to perform the dot product of the input light beam into the ICE **100** and a desired loaded regression vector represented by each layer **102**, **104** for each wavelength. As a result, the output light intensity of the ICE **100** is related to the characteristic or analyte of interest. Further details regarding how the exemplary ICE **100** is able to distinguish and process electromagnetic radiation related to the characteristic or analyte of interest are described in U.S. Pat. Nos. 6,198,531; 6,529,276; and 7,920,258.

Referring now to FIG. **2***a*, illustrated is a block diagram that non-mechanistically illustrates how an optical computing device **200** is able to distinguish electromagnetic radiation related to a characteristic of a sample **202** from other electromagnetic radiation. As shown in FIG. **2***a*, an electromagnetic radiation source **201** emits or otherwise generates electromagnetic radiation **204**. The electromagnetic radiation source **201** may be any device capable of emitting or generating electromagnetic radiation, as defined herein. In some embodiments, the electromagnetic radiation source **201** is a light bulb, light emitting device (LED), laser, blackbody, photonic crystal, or X-Ray source, or the like. The electromagnetic radiation **204** is directed toward the sample **202**, which contains an analyte of interest (e.g., a characteristic of the sample) desired to be determined. The electromagnetic radiation **204** optically interacts with the sample **202** and produces optically interacted radiation **206** (e.g., sample-interacted light), some of which may be electromagnetic radiation corresponding to the characteristic or analyte of interest and some of which may be background electromagnetic radiation corresponding to other components or characteristics of the sample **202**.

While FIG. **2***a* shows the electromagnetic radiation **204** as passing through the sample **202** to produce the optically interacted radiation **206**, it is also contemplated herein to reflect the electromagnetic radiation **204** off of the sample **202**, such as may be required when the sample **202** is translucent, opaque, or solid. Accordingly, reflecting the electromagnetic radiation **204** off of the sample **202** also generates the optically interacted radiation **206**. Moreover, in some embodiments, the electromagnetic radiation source **201** may be omitted altogether and the required electromagnetic radiation may be derived from the sample **202** itself. For example, various substances naturally radiate electromagnetic radiation. For instance, the sample **202** may be a blackbody radiating substance configured to radiate electromagnetic radiation in the form of heat. In other embodiments, the sample **202** may be radioactive or chemo-luminescent and therefore radiate electromagnetic radiation. In yet other embodiments, the required electromagnetic radiation may be induced from the sample **202** by being acted upon mechanically, magnetically, electrically, combinations thereof, or the like.

Although not specifically shown, one or more spectral elements may be employed in the device **200** in order to restrict the optical wavelengths and/or bandwidths of the system and thereby eliminate unwanted electromagnetic radiation existing in wavelength regions that have no importance. Such spectral elements can be located anywhere along the optical train, but are typically employed directly after the electromagnetic radiation source **201**. Various configurations and applications of spectral elements in optical computing devices may be found in commonly owned U.S. Pat. Nos. 6,198,531; 6,529,276; 7,123,844; 7,834,999; 7,711,605, 7,920,258, 8,049,881, and U.S. patent application Ser. No. 12/094,460 (U.S. Pat. App. Pub. No. 2009/0219538); Ser. No. 12/094,465 (U.S. Pat. App. Pub. No. 2009/0219539).

The optically interacted radiation **206** may impinge upon the optical computing device **200**, which may contain, for example, a beam splitter **208**. The beam splitter **208** may be configured to split the optically interacted radiation **206** into a first beam of light **206***a* directed in a first channel A and a second beam of light **206***b* directed in a second channel B. As used herein, the term "channel" refers generally to an optical path or optical train, as known in the art. The first channel A is configured to direct the first beam of light **206***a* toward an ICE **209**, thus the first channel A may be characterized as or otherwise called a "primary" channel. The ICE **209** may be substantially similar to the ICE **100** described above with reference to FIG. **1**. The ICE **209** may be configured to produce modified electromagnetic radiation **210** corresponding to the characteristic or analyte of interest. In particular, the modified electromagnetic radiation **210** may include electromagnetic radiation that has optically interacted with the ICE **209**, whereby approximate mimicking of the regression vector corresponding to the characteristic of interest is obtained.

Within the primary channel A, the modified electromagnetic radiation **210** is subsequently conveyed to a detector **212** for quantification. The detector **212** may be any device capable of detecting electromagnetic radiation, and may be generally characterized as an optical transducer. For example, the detector **212** may be, but is not limited to, a thermal detector such as a thermopile or photoacoustic detector, a semiconductor detector, a piezo-electric detector, a charge coupled device (CCD) detector, a video or array detector, a split detector, a photon detector (such as a photomultiplier tube), photodiodes, and/or combinations thereof, or the like, or other detectors known to those skilled in the art.

In some embodiments, the detector **212** is configured to produce an output signal **213** in the form of a voltage (or current) that corresponds to the particular characteristic of the sample **202**. In at least one embodiment, the output signal **213** produced by the detector **212** and the concentration of the characteristic of the sample **202** may be directly proportional. In other embodiments, however, the relationship may correspond to a polynomial function, an exponential function, and/or a logarithmic function, or a combination thereof.

The second beam of light **206***b* may be directed within the second channel B toward a second detector **216**. The second detector **216** may be similar to the first detector **212**, such as by being any device capable of detecting electromagnetic radiation. Without limitation, the second detector **216** may be used to detect radiating deviations stemming from the electromagnetic radiation source **201**. Undesirable radiating deviations can occur in the intensity of the light in the primary channel A due to a wide variety of reasons and causing various negative effects. These negative effects can be particularly detrimental for measurements taken over a period of time. Radiating deviations can include such things as, but not limited to, light intensity fluctuations of the electromagnetic radiation **204**. It can also include interferent fluctuations, which may scatter or absorb light from the sample **202** as it moves through the interaction space as might occur if a foreign substance such as dirt or dust is entrained within the sample **202** or otherwise passes in front of the electromagnetic radiation source **201**. Radiating deviations can also include a film of material build-up on the windows of the interrogation space which has the effect of reducing the amount of light reaching the detector **216**. Without proper compensation, such radiating deviations could result in false readings from the primary channel A, and the output signal **213** would no longer be primarily related to the characteristic of interest.

To correct or compensate for these types of undesirable effects, the second detector **216** arranged in the second channel B may be configured to generate a compensating signal **218** generally indicative of the radiating deviations of the electromagnetic radiation source **201**, and thereby normalize the output signal **213**. Accordingly, the second channel B is typically characterized as or otherwise referred to in the art as a "reference" channel. In some applications, the compensating signal **218** and the output signal **213** may be transmitted to or otherwise received by a signal processor **220** communicably coupled to both the detectors **212**, **216**. The signal processor **220** may be a computer including a non-transitory machine-readable medium, as discussed in more detail below. The signal processor **220** may be configured to computationally combine the compensating signal **218** with the output signal **213** in order to normalize the output signal **213** in view of any radiating deviations as detected by the second detector **216**. In some embodiments, computationally combining the output and compensating signals **213**, **218** may entail computing a ratio of the two signals **213**, **218**, thereby essentially computing a ratio of the primary and reference channels A and B (e.g., A/B).

It should be noted that the reference channel B is created in a manner which does not detrimentally change the predictive characteristics of ICE **209** arranged in the primary channel A. For example, if the beamsplitter **208** were replaced with a spectral element (e.g., one whose transmittance or reflectance has a variation with wavelength), then the spectral characteristics of the light incident upon the ICE **209** arranged in the primary channel A would be altered, and the light emerging from the ICE **209** would have its spectral characteristics and intensity changed from the original design, with a generally negative consequence. Viewed another way, a spectrally active element would modify the intended transmission (or reflection) spectrum of the ICE **209** which was originally and carefully designed to mimic the regression vector associated with the analyte or characteristic of interest. Thus, reference channel B is generally created by detecting a portion of the light beam before striking the ICE **209**. Spectrally neutral elements (e.g., elements whose transmittance, absorbance, and/or reflectance do not vary substantially with wavelength) are generally used to create the reference channel B. At least some spectrally neutral elements that may be used are, but are not limited to, neutral density filters and beamsplitters, partially transparent masks, front surface Fresnel reflections, combinations thereof, or similar components.

The signal processor **220** may also be configured to further process the output and compensating signals **213**, **218** in order to provide additional characterization information about the sample **202** being analyzed. In some embodiments, the identification and concentration of each analyte in the sample **202** can be used to predict certain physical characteristics of the sample **202**. For example, the bulk characteristics of a sample **202** can be estimated by using a combination of the properties conferred to the sample **202** by each analyte.

In some embodiments, the concentration of each analyte or the magnitude of each characteristic determined using the optical computing device **200** can be fed into an algorithm run by the signal processor **220**. The algorithm may be configured to make predictions on how the characteristics of the sample **202** change if the concentrations of the analytes are changed relative to one another. In some embodiments, the algorithm produces an output that is readable by an operator who can consider the results and make proper adjustments or take appropriate action, if needed, based upon the output.

The algorithm can be part of an artificial neural network configured to use the concentration of each detected analyte in order to evaluate the characteristic(s) of the sample **202** and, if desired, predict how to modify the sample **202** in order to alter its properties in a desired way. Illustrative but non-limiting artificial neural networks are described in commonly owned U.S. patent application Ser. No. 11/986,763 (U.S. Patent App. Pub. No. 2009/0182693). It is to be recognized that an artificial neural network can be trained using samples having known concentrations, compositions, and/or properties, thereby generating a virtual library. As the virtual library available to the artificial neural network becomes larger, the neural network can become more capable of accurately predicting the characteristics of a sample having any number of analytes present therein. Furthermore, with sufficient training, the artificial neural network can more accurately predict the characteristics of the sample, even in the presence of unknown analytes.

It is recognized that the various embodiments herein directed to computer control and artificial neural networks, including various blocks, modules, elements, components, methods, and algorithms, can be implemented using computer hardware, software, combinations thereof, and the like. To illustrate this interchangeability of hardware and software, various illustrative blocks, modules, elements, components, methods and algorithms have been described generally in terms of their functionality. Whether such functionality is implemented as hardware or software will depend upon the particular application and any imposed design constraints. For at least this reason, it is to be recognized that one of ordinary skill in the art can implement the described functionality in a variety of ways for a particular application. Further, various components and blocks can be arranged in a different order or partitioned differently, for example, without departing from the scope of the embodiments expressly described.

Computer hardware used to implement the various illustrative blocks, modules, elements, components, methods, and algorithms described herein can include a processor configured to execute one or more sequences of instructions, programming stances, or code stored on a non-transitory, computer-readable medium. The processor can be, for example, a general purpose microprocessor, a microcontroller, a digital signal processor, an application specific integrated circuit, a field programmable gate array, a programmable logic device, a controller, a state machine, a gated logic, discrete hardware components, an artificial neural network, or any like suitable entity that can perform calculations or other manipulations of data. In some embodiments, computer hardware can further include elements such as, for example, a memory [e.g., random access memory (RAM), flash memory, read only memory (ROM), programmable read only memory (PROM), erasable read only memory (EPROM)], registers, hard disks, removable disks, CD-ROMS, DVDs, or any other like suitable storage device or medium.

Executable sequences described herein can be implemented with one or more sequences of code contained in a memory. In some embodiments, such code can be read into the memory from another machine-readable medium. Execution of the sequences of instructions contained in the memory can cause a processor to perform the process steps described herein. One or more processors in a multi-processing arrangement can also be employed to execute instruction sequences in the memory. In addition, hard-wired circuitry can be used in place of or in combination with software instructions to implement various embodiments described herein. Thus, the present embodiments are not limited to any specific combination of hardware and/or software.

As used herein, a machine-readable medium refers to any medium that directly or indirectly provides instructions to a processor for execution. A machine-readable medium can take on many forms including, for example, non-volatile media, volatile media, and transmission media. Non-volatile media can include, for example, optical and magnetic disks. Volatile media can include, for example, dynamic memory. Transmission media can include, for example, coaxial cables, wire, fiber optics, and wires that form a bus. Common forms of machine-readable media can include, for example, floppy disks, flexible disks, hard disks, magnetic tapes, other like magnetic media, CD-ROMs, DVDs, other like optical media, punch cards, paper tapes and like physical media with patterned holes, RAM, ROM, PROM, EPROM and flash EPROM.

In some embodiments, the data collected using the optical computing devices can be archived along with data associated with operational parameters being logged at a job site. Evaluation of job performance can then be assessed and improved for future operations or such information can be used to design subsequent operations. In addition, the data and information can be communicated (wired or wirelessly) to a remote location by a communication system (e.g., satellite communication or wide area network communication) for further analysis. The communication system can also allow remote monitoring and operation of a process to take place. Automated control with a long-range communication system can further facilitate the performance of remote job operations. In particular, an artificial neural network can be used in some embodiments to facilitate the performance of remote job operations. That is, remote job operations can be conducted automatically in some embodiments. In other embodiments, however, remote job operations can occur under direct operator control, where the operator is not at the job site.

Referring to FIG. **2***b*, illustrated is an exemplary variation of the optical computing device **200** described above with reference to FIG. **2***a*. In FIG. **2***b*, the beam splitter is replaced with the ICE **209** which now essentially functions like a beam splitter. Specifically, the optically interacted radiation **206** may impinge upon the ICE **209** which may be configured to transmit a first modified electromagnetic radiation **210** in the primary channel A and reflect a second modified electromagnetic radiation **222** in the reference channel B. Each of the first and second modified electromagnetic radiations **210**, **222** may correspond to the characteristic or analyte of interest. In particular, the modified electromagnetic radiations **210**, **222** may each include electromagnetic radiation that has optically interacted with the ICE **209**, whereby approximation mimicking of the regression vector corresponding to the characteristic of interest is obtained. In use, however, the signal from the reference channel B may be used to normalize the signal from the primary channel A, as generally described above.

For instance, the first detector **212** receives the first modified electromagnetic radiation **210** and provides the output signal **213** to the signal processor **220**, and the second detector **216** receives the second modified electromagnetic radiation **222** and provides the compensating signal **218** to the signal processor. The signal processor **220** computationally combines the compensating signal **218** with the output signal **213** in order to normalize the output signal **213** in view of any radiating deviations as detected by the second detector **216**. In the illustrated embodiment, where the second modified electromagnetic radiation **222** also provides an approximate mimicking of the regression vector corresponding to the characteristic of interest, computationally combining the output and compensating signals **213**, **218** may entail computing a ratio of the output signal **210** and the sum of the output signal **210** and the compensating signal **218**. In other words, the signal processor **220** may be configured to compute the ratio of the signal derived from the primary channel A and the sum of the signals derived from both the primary and compensating channels A,B (i.e., A/(A+B)).

Referring now to FIG. **3***a*, illustrated is another optical computing device **300** also configured to determine a characteristic of interest of the sample **202**. The optical computing device **300** may be similar in several respects to the optical computing device **200** described above with reference to FIGS. **2***a* and **2***b*. Accordingly, the device **300** may be best understood with reference to FIGS. **2***a* and **2***b*, where like numerals represent like elements that will not be described again in detail. Similar to the device **200** discussed above, the optical computing device **300** receives an output of optically interacted radiation **206** emitted from the sample **202** after the sample **202** has been illuminated with electromagnetic radiation **204** from the electromagnetic radiation source **201**. Unlike the optical computing device **200**, however, the optical computing device **300** may include at least two ICEs, illustrated as a first ICE **302** and a second ICE **304**. The first and second ICE **302**, **304** may be generally similar in construction to the ICE **100** described above with reference to FIG. **1**, but may also vary from each other depending on the application, as will be better understood from the discussion below.

In some embodiments, the first and second ICE **302**, **304** may be configured to be associated with a particular characteristic of the sample **202**. In other words, the first and second ICE **302**, **304** may be especially designed in their respective layers, thicknesses, and materials so as to correspond with the spectral attributes associated with the characteristic of interest. Each of the first and second ICE **302**, **304**, however, may be designed entirely different from each other, thereby approximating or otherwise mimicking the regression vector of the characteristic in entirely different ways. In other embodiments, however, one or both of the first and second ICE **302**, **304** may be entirely or substantially disassociated with the characteristic of interest. Briefly, manufacturing an ICE can be a very complex and intricate process. In addition, when an ICE is manufactured specifically to mimic the regression vector of a characteristic of interest, this process can become even more complicated. As a result, it is common to produce non-predictive, or poorly made ICE that, when tested, fail to accurately or even remotely be associated with the characteristic of interest (e.g., a disassociated ICE). In some cases, these non-predictive ICE may return an arbitrary regression vector when tested or otherwise exhibit an arbitrary transmission function. In other cases, the non-predictive ICE may be considered "substantially" disassociated with the characteristic of interest in that the ICE only slightly mimics the regression vector of the characteristic but is nonetheless considered non-predictive. In yet other cases, the non-predictive ICE may return a regression vector that closely mimics another characteristic of the substance being tested, but not the characteristic of interest.

Additional information and advantages of using multiple associated or disassociated ICE in optical computing devices to determine a single characteristic of interest is further described in co-pending U.S. Pat. App. Pub. Nos. 2013/0284895 and 2013/0284896.

As shown in FIG. **3***a*, the optically interacted radiation **206** is directed to the optical computing device **300** and the beam splitter **208** again separates the optically interacted radiation **206** into first and second beams of light **206***a*,*b*. The first beam of light **206***a* is directed into the first or primary channel A**1** and conveyed to the first ICE **302** which generates a first modified electromagnetic radiation **306** corresponding to the characteristic or analyte of interest of the sample **202**. The first detector **212** may be arranged to receive the first modified electromagnetic radiation **306** from the first ICE **302** and quantify the resulting signal in the form of a first output signal **310**.

As illustrated, the second ICE **304** is arranged within what would normally be used as a reference channel configured to normalize the first output signal **310** derived from the primary channel A**1** in view of radiating deviations of the electromagnetic radiation source **201**. Arranging the second ICE **304** in the typical reference channel, however, now provides a new type of reference channel A**2** and, similar to the primary channel A**1**, the reference channel A**2** is also configured to provide an output corresponding to the characteristic or analyte of interest of the sample **202**. Consequently, the reference channel A**2** may also be considered, in at least some cases, as a primary channel of the device **300**, substantially similar to the first primary channel A**1**. As will discussed below, embodiments are contemplated herein which include several primary "A" channels in a single optical computing device, where each primary "A" channel is configured to provide an output corresponding to the characteristic or analyte of interest of the sample **202**.

In FIG. **3***a*, the second beam of light **206***b* is directed into the reference channel A**2** and conveyed to the second ICE **304** which generates a second modified electromagnetic radiation **308** corresponding to the characteristic or analyte of interest of the sample **202**. The second detector **216** may be arranged to receive the second modified electromagnetic radiation **308** from the second ICE **304** and quantify the resulting signal in the form of a second output signal **312**.

As illustrated, the optical computing device **300** may further include a third detector **314**, according to one or more embodiments. The third detector **314** may be substantially similar to the first and second detectors **212**, **216** and may be used in the device **300** to detect radiating deviations stemming from the electromagnetic radiation source **201**. Accordingly, a second or true reference channel B may be included in the device **300** and may serve the same purpose as the reference channel B described above with reference to FIGS. **2***a* and **2***b*. As illustrated, a beam splitter **316** may be arranged to reflect a portion of the optically interacted light **206** toward the third detector **314** in order to generate a compensating signal **318** generally indicative of radiating deviations, as generally described above. In other embodiments, however, the third detector **314** may be arranged so as to receive electromagnetic radiation **204** directly from the electromagnetic source **201** or electromagnetic radiation reflected off of either of the ICE **302**, **304** and likewise generate the compensating signal **318**.

The first and second output signals **310**, **312** may then be received by and computationally combined in the signal processor **220** to determine the characteristic of interest in the sample **202**. In one or more embodiments, computationally combining the first and second output signals **310**, **312** is desired. This computation may involve a variety of mathematical relationships, including, for example, a linear relationship, a polynomial function, an exponential function, and or a logarithmic function, or a combination thereof. In these cases, a variety of normalization mathematics between the output signals **310**, **312** and the compensating signal **318** may be applied in order to take into account any radiating deviations detected by the third detector **314**. For example, the output signals **310**, **312** may each be normalized by dividing each by the compensating signal **318** to achieve, for example, A**1**/B and A**2**/B, before the mathematical relationship between A**1**/B and A**2**/B is applied. In other cases, the mathematical relationship between A1 and A2 may be applied, with the resultant normalized by channel B. In even other cases, a combination of these two normalization methods may be applied. Those skilled in the art will be familiar with both general methods, and can choose which method is most applicable given the specific relationships involved. Finally, it is understood by those skilled in the art that fractions or multiples of the quantity B may be employed, as well as multiplication of the quantity (1/B).

Referring now to FIG. **3***b*, illustrated is another exemplary optical computing device **320**, according to one or more embodiments. The device **320** may be substantially similar to the device **300** described above with reference to FIG. **3***a* and therefore may be best understood with reference thereto, where like numerals represent like elements not described again in detail. In FIG. **3***b*, the optically interacted radiation **206** is again directed into the first or primary channel A**1** and conveyed to the first ICE **302** which generates a first modified electromagnetic radiation **306** corresponding to the characteristic or analyte of interest of the sample **202**. The first detector **212** receives the first modified electromagnetic radiation **306** from the first ICE **302** and provides the first output signal **310**.

The second ICE **304** may again be arranged within what could normally be used as a reference channel for the device **320** and otherwise used to normalize the first output signal **310** derived from the primary channel A**1** in view of radiating deviations of the electromagnetic radiation source **201**. Specifically, the second ICE **304** is arranged in new reference channel A**2** and, similar to the primary channel A**1**, may be configured to provide an output corresponding to the characteristic or analyte of interest of the sample **202**. As depicted, the second ICE **304** may be configured to optically interact with a portion of the electromagnetic radiation **204** directly radiated by the electromagnetic radiation source **201**. In one or more embodiments, a beam splitter **322** may be configured to split the electromagnetic radiation **204** and direct a portion thereof toward the second ICE **304**. In other embodiments, however, the second ICE **304** may be arranged so as to receive the electromagnetic radiation **204** directly from the electromagnetic radiation source **201**, instead of receiving a reflected portion thereof. Those skilled in the art will readily recognize that the reference channel A**2** may be defined in a variety of locations within the optical computing device **320**, or any of those described herein, without departing from the scope of the disclosure.

The second ICE **304** generates the second modified electromagnetic radiation **308** and conveys the same to the second detector **216**. The second detector **216** may be configured to receive and quantify the second electromagnetic radiation **308** and provide the second output signal **312** which may be directed toward the signal processor **220**.

As illustrated, the optical computing device **320** may further include the third detector **314** used to detect radiating deviations stemming from the electromagnetic radiation source **201**. In one embodiment, the third detector **314** may be arranged to receive a portion of the optically interacted light **206** as reflected from the beam splitter **316**. In other embodiments, however, the third detector **314** may be arranged to receive a portion of the electromagnetic radiation **204** as reflected from another beam splitter **324** arranged within the reflected portion of the electromagnetic radiation **204** as derived from the first beam splitter **322**. Accordingly, a true reference channel B may also be included in the device **300** and may serve the same purpose as the reference channel B described above with reference to FIGS. **2***a* and **2***b*. As illustrated, a beam splitter **316** may be arranged to reflect a portion of the optically interacted light **206** toward the third detector **314** in order to generate a compensating signal **318** generally indicative of radiating deviations, as generally described above.

The compensating signal **318** in the second reference channel B may be directed to the signal processor **220** and computationally combined with the first and second output signals **310**, **312** derived from the primary and first reference channels A**1**, A**2**, respectively, in order to compensate for any electromagnetic radiating deviations stemming from the electromagnetic radiation source **201**. As discussed above, the ratio of the light intensity derived from the primary and first reference channels A**1**, A**2** is divided by the light intensity derived from the second reference channel B, and the resulting output is related to the analyte concentration or characteristic of interest. In one embodiment, for example, the compensating signal **318** and the first and second output signals **310**, **312** are combined using principal component analysis techniques such as, but not limited to, standard partial least squares which are available in most statistical analysis software packages (e.g., XL Stat for MICROSOFT® EXCEL®; the UNSCRAMBLER® from CAMO Software and MATLAB® from MATHWORKS®). In other embodiments, the compensating signal **318** is used simply to inform the user of the condition of the electromagnetic radiation source **201**, e.g., whether the source **201** is functioning properly.

As will be appreciated by those skilled in the art, more than two ICE **302**, **304** may be used in alternative configurations or embodiments, without departing from the scope of the disclosure. Moreover, it should be noted that while FIGS. **3***a* and **3***b* show electromagnetic radiation as being transmitted through the first and second ICE **302**, **304** in order to generate the first and second modified electromagnetic radiations **306**, **308**, respectively, it is also contemplated herein to reflect the electromagnetic radiation off of the first and second ICE **302**, **304** and equally generate the corresponding first and second modified electromagnetic radiations **306**, **308**, without departing from the scope of the disclosure.

It has been discovered that usage of one or more ICE in both the primary and reference channels A**1**, A**2** may enhance the sensitivity and detection limits of the optical computing device **300** beyond what would otherwise be attainable with a single ICE design that utilizes a dedicated reference channel B for normalizing electromagnetic radiation fluctuations, such as is described above with reference to FIGS. **2***a* and **2***b*. This was entirely unexpected and would be considered wholly unobvious to those skilled in the art. For instance, the typical reference channel B in optical computing devices is a spectrally neutral channel and therefore dedicated solely to providing a ratio denominator useful in normalizing the output signal derived from the primary channel A against radiating deviations. Placing an ICE in the reference channel B would be wholly unobvious since the ICE is designed to be spectrally active and therefore has a spectrum associated with it which optically interacts with the second light beam **206***b* and changes its spectral characteristics. Accordingly, with the second ICE **304** arranged in the reference channel A**2**, as depicted in FIG. **3***a*, the reference channel is no longer used for its intended purpose but nonetheless has been found to dramatically increase the sensitivities and detection limits of the device **300**. These unexpected results are especially possible even in the presence of various interferents.

As further explanation, methods of how to design and build single ICE elements with optimal performance characteristics are disclosed in U.S. Pat. No. 7,711,605 and U.S. Pat. Pub. No. 2010/0153048. Using the methods described therein, literally thousands and hundreds of thousands of individual unique designs are created and optimized for performance, thereby exhausting the optimal solution space available and yielding the best solutions possible. Those skilled in the art will readily recognize that ICE designs can be particularly sensitive to small changes in their optical characteristics. Thus, any modification of the optical characteristic (e.g., changes made to the particular transmission function) with, for example, additional ICE components, would be considered as degrading the performance of the optical computing device, and in most cases, quite rapidly with only small changes. And indeed, it has been discovered that spectral components (i.e., ICE components or designs) arranged in the reference channel B do degrade the overall performance in some instances.

However, it was unexpectedly discovered that, in at least some case, some spectral components, including some preferred ICE designs, may enhance overall device performance when arranged in the reference channel B. It was further discovered, that these enhancements are not minor adjustments or improvements, but may enhance performance involving factors and/or orders of magnitude of improvement. It was yet further discovered that performance enhancements can be obtained without substantial compromise or trade-off of other important characteristics. It was also discovered that the ICE arranged in the reference channel B may or may not be configured to be associated with the characteristic of the sample.

Referring to FIG. **4**, illustrated is a graph **400** indicating the detection of a particular characteristic of a sample using one ICE arranged in the primary channel A, and another ICE in the reference channel B. It will be appreciated that the graph **400** and the data presented therein are merely used to facilitate a better understanding of the present disclosure, and in no way should the they be read to limit or define the scope of the invention. The graph **400** indicates the detection of the methane gas to oil ratio (GOR) in two radically different oils from concentrations from 0 to 1000 scuft/bbl (standard cubic feet per standard barrel) under various pressures and temperatures associated with downhole oil field conditions. The two oils are a black, high asphaltene content optically opaque oil sample obtained from the Gulf of Mexico, and a light, low asphaltene, relatively transparent, high sulfur content oil sample obtained from Saudi Arabia. The graph **400** depicts the accuracy (standard deviation) of measuring the GOR for both oils across the entire 0 to 1000 scuft/bbl concentration range of interest for an optical computing device (e.g., the optical device **300**, or any of the exemplary optical computing devices disclosed herein) on the X-axis.

Results are shown for five different individual ICE designs and with the various unique combinations of the five with one of the ICE designs in the reference channel B. As shown, a single ICE design without an ICE in the reference channel B (i.e., shown as triangles) may yield an accuracy ranging between a predictive 19.2% of full scale (190 scuft/bbl) and a non-predictive 34.9% of full scale (349 scuft/bbl).

The sensitivity of the device (e.g., the optical device **300**, or any of the exemplary optical computing devices disclosed herein), another key performance attribute important to the detection limits, is also shown in the graph on the Y axis. The units of sensitivity are the absolute magnitude of the % change in detector signal output observed over the entire GOR concentration range (0 to 1000 scuft/bbl) of interest. Regarding sensitivity, the larger the magnitude of the % change, the more sensitive and desirable is the system as greater sensitivity can enable better detectability and performance limits, lower costs, and other important benefits. As shown, sensitivities for the standard configuration involving a neutral reference channel B, but without an ICE arranged in the reference channel B (i.e., shown as triangles), range from 3.3% to 4.9%.

When an ICE design is arranged in the reference channel B, however, the performance may be enhanced (i.e., shown as squares). For example, by placing an ICE in the reference channel B, accuracies may be improved from a non-predictive 34.9% (349 scuft/bbl) to a highly predictive 1.1% (11 scuft/bbl), or about a factor of 17× improvement over the best single ICE with neutral reference case, and about a factor of 31× over the non-predictive case. Sensitivities were also improved for many combinations, obtaining a factor of between 1.5 to almost 3× of that of a single ICE design without a spectral element (i.e., additional ICE) in the reference channel.

Those skilled in the art will readily recognize that increases in sensitivity are often accompanied by corresponding decreases in accuracy for single ICE solutions. Thus, one single ICE design may have superior sensitivity over another, but will generally be found to be less accurate. Accuracy and sensitivity, two of the most important performance parameters for optical computing devices, are therefore generally trade-offs. The improvement in accuracy discovered by using an ICE in the reference channel B, as shown in FIG. **4**, was totally unexpected. Even more unexpected was that both the accuracy and sensitivity could be simultaneously increased or at least maintained. For example, three of the unique combinations with an ICE in the reference channel B show both a dramatic enhancement in accuracy and an improvement of approximately 1.5 to 3× in sensitivity. Three showed a substantial improvement in sensitivity (and therefore lower detection limits) while maintaining about the same accuracy.

It should be noted that these unexpected results were not achieved for all combinations of ICE designs in the reference channel B. Instead, there were three combinations, in particular, where the accuracy improved but the sensitivity decreased. Moreover, one combination was tested where the accuracy was not improved, but the sensitivity decreased. However, the graph **400** clearly shows that optical computing device performance can increase by placing a spectral component (e.g., an ICE design) in the reference channel B as opposed to using the traditional non-spectral component. Moreover, the ICE arranged in the reference channel B could either be associated (predictive) or substantially disassociated (non-predictive) with the characteristic of interest (GOR in this case).

Referring now to FIG. **5**, illustrated is another exemplary optical computing device **500**, according to one or more embodiments. The device **500** may be somewhat similar to the optical computing device **300** described above with reference to FIG. **3***a*, and therefore may be best understood with reference to FIG. **3***a* where like numerals indicate like elements that will not be described again in detail. As illustrated, the device **500** may include a first ICE **502** and a second ICE **504**. The first and second ICE **502**, **504** may be similar in construction to the ICE **100** described above with reference to FIG. **1**, and configured to be either associated or disassociated with a particular characteristic of the sample. Embodiments are contemplated herein that include one or more beam splitters, mirrors, and the like in order to allow the electromagnetic radiation **204** to optically interact with both the sample **202** and first and second ICE **502**, **504**, without departing from the scope of the disclosure. Indeed, one or more beam splitters, mirrors, and the like may be used in conjunction with any of the exemplary embodiments disclosed herein, without departing from the scope of the disclosure.

As illustrated, the first and second ICE **502**, **504** may be coupled together to form a monolithic structure, but in other embodiments may be separated or otherwise arranged in series without departing from the scope of the disclosure. Moreover, the first and second ICE **502**, **504** may be arranged to receive the optically interacted light **206**, as depicted, but may equally be arranged antecedent to the sample **202** and therefore directly receive the electromagnetic radiation **204**. In one embodiment, the first ICE **502** may be smaller than the second ICE **504** or otherwise arranged such that a portion of the optically interacted light **206** passes through only the second ICE **504** and generates the first modified electromagnetic radiation **306**. Another portion of the optically interacted light **206** may pass through a combination of both the first and second ICE **502**, **504** and thereby generate the second modified electromagnetic radiation **308**. As a result, the device **500** may provide a first or primary channel **A1** that incorporates the optically interacted light **206** passing through the second ICE **504** and thereafter generating the first modified electromagnetic radiation **306**, and a second or reference channel **A2** that incorporates the optically interacted light **206** passing through both the first and second ICE **502**, **504** and thereafter generating the second modified electromagnetic radiation **308**.

The first and second modified electromagnetic radiations **306**, **308** may be directed to a detector **506**, which may be a split or differential detector, having a first detector portion **506***a* and a second detector portion **506***b*. In other embodiments, however, the detector **506** may be a detector array, as known in the art, without departing from the scope of the disclosure. In operation, the first detector portion **506***a* forms part of the primary channel A**1** and may be configured to receive the first modified electromagnetic radiation **306** and generate a first output signal **508***a*. Furthermore, the second detector portion **506***b* forms part of the reference channel A**2** and may be configured to receive the second modified electromagnetic radiation **308** and generate a second output signal **508***b*. In some embodiments, the detector **506** may be configured to computationally combine the first and second signals **508***a,b* in order to determine the characteristic of the sample, for example when using a differential detector or quad-detector. In other embodiments, the first and second signals **508***a,b* may be transmitted to or otherwise received by the signal processor **220** communicably coupled to the detector **506** and configured to computationally combine the first and second output signals **508***a,b* in order to determine the characteristic of the sample **202**. Again, computationally combining the first and second signals **508***a,b* may entail determining the ratio of the two signals, such that a ratio of the primary channel A**1** against the reference channel A**2** is obtained. In some embodiments, the signal processor **220** may be a computer including a non-transitory machine-readable medium, as generally described above.

In at least one embodiment, the device **500** may further include a second detector **510** that may function similarly to the third detector **314** described above with reference to FIG. **3***a*, and thereby further provide a second or true reference channel B. In operation, the detector **510** may be arranged to receive and detect optically interacted light **512** in order to generate the compensating signal **318** generally indicative of radiating deviations of the electromagnetic radiation source **201**. The compensating signal **318** may be directed to the signal processor **220** and computationally combined with the first and second output signals **310**, **312** in order to compensate for any electromagnetic radiating deviations stemming from the electromagnetic radiation source **201**.

It should be noted that even though the electromagnetic radiation **204** is shown in FIG. **5** as optically interacting with the sample **202** before reaching the first and second ICE **502**, **504**, the first and second ICE **502**, **504** nonetheless are considered to have optically interacted with the electromagnetic radiation **204**, albeit subsequent to the sample **202**. In other embodiments, the electromagnetic radiation **204** may optically interact with the first and second ICE **502**, **504** before reaching the sample **202**, and the sample **202** nonetheless is considered to have optically interacted with the electromagnetic radiation **204**, albeit subsequent to the first and second ICE **502**, **504**. Furthermore, embodiments are contemplated herein where the first ICE **502** is arranged on one side of the sample **202**, and the second ICE **504** is arranged on the opposite side of the sample **202**. As a result, the electromagnetic radiation **204** may optically interact with the first ICE **502** prior to optically interacting with the sample **202**, and subsequently optically interacting with the second ICE **504**. It will be appreciated that any and all of the embodiments disclosed herein may include any of the exemplary variations discussed herein, such as arranging the sample **202** before or after the first and second ICE **502**, **504**, or arranging the ICE **502**, **504** in linear or non-linear configurations.

Referring now to FIG. **6**, with continued reference to FIG. **5**, illustrated is another optical computing device **600**, according to one or more embodiments. The device **600** may be somewhat similar to the optical computing device **500** described with reference to FIG. **5**, therefore the device **600** may be best understood with reference thereto, where like numerals indicate like elements. The device **600** may include a first ICE **602** and a second ICE **604** similar in construction to the ICE **100** described above with reference to FIG. **1**, and configured to be either associated or disassociated with a particular characteristic of the sample **202**, such as is described above with reference to the first and second ICE **302**, **304** of FIG. **3***a*.

As illustrated, the first and second ICE **602**, **604** may be arranged generally parallel relative to one another and configured to receive the optically interacted light **206**. As with prior embodiments, however, the first and second ICE **602**, **604** may equally be arranged antecedent to the sample **202**, without departing from the scope of the disclosure. In operation, the first ICE **602** may receive a portion of the optically interacted light **206** and thereby generate the first modified electromagnetic radiation **306**. The second ICE **604** may be configured to receive another portion of the optically interacted light **206** and thereby generate the second modified electromagnetic radiation **308**. As a result, the device **600** may provide a first or primary channel A**1** that incorporates the optically interacted light **206** passing through the first ICE **602** and thereafter generating the first modified electromagnetic radiation **306**, and a second or reference channel A**2** that incorporates the optically interacted light **206** passing through the second ICE **604** and thereafter generating the second modified electromagnetic radiation **308**.

The first and second modified electromagnetic radiations **306**, **308** may be directed to the detector **506** to generate the first output signal **508***a* in the primary channel A**1** and the second output signal **508***b* in the reference channel A**2** as corresponding to the first and second modified electromagnetic radiations **306**, **308**, respectively. Specifically, the first detector portion **506***a* may be configured to receive the first modified electromagnetic radiation **306** and generate the first output signal **508***a*, and the second detector portion **506***b* may be configured to receive the second modified electromagnetic radiation **308** and generate the second output signal **508***b*. In some embodiments, the detector **506** may be configured to computationally combine the first and second output signals **508***a,b* in order to determine the characteristic of the sample. In other embodiments, however, the first and second signals **508***a,b* may be received by a signal processor **220** communicably coupled to the detector **506** and configured to computationally combine the first and second signals **508***a,b* in order to determine the characteristic of the sample.

In some embodiments, the detector **506** is a single detector but configured to time multiplex the first and second modified electromagnetic radiations **306**, **308**. For example, the first ICE **602** may be configured to direct the first modified electromagnetic radiation **306** toward the detector **506** at a first time T**1**, and the second ICE **604** may be configured to direct the second modified electromagnetic radiation **308** toward the detector **506** at a second time T**2**, where the first and second times T**1**, T**2** are distinct time periods that do not spatially overlap. Consequently, the detector **506** receives at least two distinct beams of modified electromagnetic radiation **306**, **308** which may be computationally combined by the detector **506** in order to provide an output in the form of a voltage that corresponds to the characteristic of the sample.

In one or more embodiments, in order to provide the first and second times T**1**, T**2**, the device **600** may include more than one electromagnetic radiation source **201**. In other embodiments, the electromagnetic radiation source **201** may be pulsed in order to provide the first and second times T**1**, T**2**. In yet other embodiments, each ICE **602**, **604** may be mechanically positioned to interact with the electromagnetic radiation beam at two distinct times. In yet other embodiments, the electromagnetic radiation beam may be deflected, or diffracted to interact with the two different ICE elements at times T**1** and T**2**. Moreover, it will be appreciated that more than the first and second ICE **602**, **604** may be used, thereby generating additional primary channels (e.g., A**3**, A**4**, . . . An), and the detector **506** may therefore be configured to time multiplex each additional beam of optically interacted light to provide the cumulative voltage corresponding to the characteristic of the sample.

In at least one embodiment, the device **600** may further include the second detector **510** that may function similarly to the third detector **314** described above with reference to FIG. **3***a*, and thereby further provide a second or true reference channel B. As illustrated, a beam splitter **606** may be arranged to reflect a portion of the optically interacted light **206** toward the second detector **510** in order to generate a compensating signal **318** generally indicative of radiating deviations of the electromagnetic radiation source **201**. In other embodiments, however, the second detector **510** may be arranged so as to receive electromagnetic radiation **204** directly from the electromagnetic source **201** or electromagnetic radiation reflected off of either of the ICE **302**, **304** and likewise generate the compensating signal **318**. The compensating signal **318** may be directed to the signal processor **220** and computationally combined with the first and second output signals **310**, **312** in order to compensate for any electromagnetic radiating deviations stemming from the electromagnetic radiation source **201**. As a result, a second reference channel B may be included in the device **300** and employed substantially similarly to the reference channel B described above with reference to FIGS. **2***a* and **2***b*. In other embodiments, the compensating signal **318** may be used to inform the user of the condition of the electromagnetic radiation source **201**, e.g., whether the source **201** is functioning properly.

Referring now to FIG. **7**, illustrated is another optical computing device **700**, according to one or more embodiments. The device **700** may be somewhat similar to the optical computing devices **500**, **600** described with reference to FIGS. **5** and **6** and therefore the device **700** may be best understood with reference thereto, where like numerals indicate like elements. The device **700** may include at least two ICE, including a first ICE **702***a* and a second ICE **702***b*, but may further include one or more additional ICE **702***n*. Each ICE **702***a-n* may be similar in construction to the ICE **100** described above with reference to FIG. **1**, and configured to be either associated or disassociated with a particular characteristic of the sample **202**, such as is described above with reference to the first and second ICE **302**, **304** of FIG. **3***a*. The device **700** may further include a plurality of detectors, such as a first detector **704***a*, a second detector **704***b*, and one or more additional detectors **704***n*.

The first, second, and additional ICE **702***a-n* may each be arranged in series relative to one another and configured to optically interact with the electromagnetic radiation **204** either through the sample **202** or through varying configurations of reflection and/or transmission between adjacent ICE **702***a-n*. In the embodiment specifically depicted, the first ICE **702***a* may be arranged in a first primary channel A**1** to receive the optically interacted radiation **206** from the sample **202**. As with prior embodiments, however, the first ICE **702***a* may equally be arranged antecedent to the sample **202**, and therefore optically interact with the electromagnetic radiation **204**. The first ICE **702***a* may be configured to transmit a modified electromagnetic radiation **706***a* to the first detector **704***a* and simultaneously convey via reflection optically interacted light **708** toward the second ICE **702***b*. The second ICE **702***b* may be arranged in a second primary channel A**2** and configured to convey a second optically interacted light **706***b* via reflection toward the second detector **704***b*, and simultaneously transmit additional optically interacted light **710** toward the additional ICE **702***n*.

The additional ICE **702***n* may be arranged within a reference channel A**3**, which would otherwise be used to detect radiating deviations of the electromagnetic radiation source **201**, but now is used to help determine the characteristic of the sample **202**. Accordingly, the reference channel A**3** may function substantially similarly to one of the primary channels A**1**, A**2**. In operation, the additional ICE **702***n* may be configured to convey an additional modified electromagnetic radiation **706***n* via reflection toward the additional detector **704***n*.

Those skilled in the art will readily recognize numerous alternative configurations of the first, second, and additional ICE **702***a-n* and corresponding first and second primary channels A**1**, A**2** and the reference channel A**3**, without departing from the scope of the disclosure. For example, reflection of optically interacted light from a particular ICE may be replaced with transmission of optically interacted light, or alternatively configurations may include the use of mirrors or beam splitters configured to direct the electromagnetic radiation **204** (or optically interacted radiation **206**) to each of the first, second, and additional ICE **702***a-n*.

In at least one embodiment, the device **700** may further include the second detector **510** that may function similarly to the third detector **314** described above with reference to FIG. **3***a*, and thereby further provide a second or true reference channel B. As illustrated, the detector **510** receives and detects optically interacted light transmitted through the additional ICE **702***n* and subsequently outputs the compensating signal **318** indicative of electromagnetic radiating deviations. In at least one embodiment, the second detector **510** may be communicably coupled to the signal processor **220** such that the compensating signal **318** may be provided or otherwise conveyed thereto.

The first, second, and additional detectors **704***a-n* may be configured to detect the first, second, and additional modified electromagnetic radiation **706***a-n*, respectively, within the corresponding first and second primary channels A**1**, A**2** and the reference channel A**3** and thereby generate a first output signal **508***a*, a second output signal **508***b*, and one or more additional output signals **508***n*, respectively. In some embodiments, the first, second, and additional output signals **508***a-n* may be received by the signal processor **220** communicably coupled to each detector **704***a-n* and configured to computationally combine the first, second, and additional signals **508***a-n* in order to determine the characteristic of the sample **202**.

This computation may involve a variety of mathematical relationships, including, for example, a linear relationship, a polynomial function, an exponential function, and/or a logarithmic function, or a combination thereof. In these cases, a variety of normalization mathematics between the output signals **508***a*, **508***b* . . . **508***n* and the compensating signal **318** may be applied. For example, the output signals **508***a*, **508***b* . . . **508***n* may each be normalized by dividing them each by the compensating signal **318** to achieve, for example, A**1**/B, A**2**/B . . . A**3**/B, before the mathematical relationship between A**1**/B and A**2**/B is applied. In other cases, the mathematical relationship between A**1** and A**2** may be applied, with the result normalized by B. In even other cases, a combination of these two normalization methods may be applied.

Those skilled in the art will be familiar with both general methods, and can choose which method is most applicable given the specific relationships involved. In one embodiment, for example, the compensating signal **318** and the output signals **508***a*, **508***b*, . . . **508***n* are combined using principal component analysis techniques such as, but not limited to, standard partial least squares which are available in most statistical analysis software packages (e.g., XL Stat for MICROSOFT® EXCEL®; the UNSCRAMBLER® from CAMO Software and MATLAB® from MATHWORKS®). Finally, it is understood by those skilled in the art that fractions or multiples of the quantity B may be employed, as well as multiplication of the quantity (1/B).

As will be appreciated, any number of ICE may be arranged within any number of primary channels or otherwise used in series in order to determine the characteristic of the sample **202**. In some embodiments, each of the first, second, and additional ICE **702***a-n* may be specially-designed to detect the particular characteristic of interest or otherwise be configured to be associated therewith. In other embodiments, however, one or more of the first, second, and additional ICE **702***a-n* may be configured to be disassociated with the particular characteristic of interest, and/or otherwise may be associated with an entirely different characteristic of the sample **202**. In yet other embodiments, each of the first, second, and additional ICE **702***a-n* may be configured to be disassociated with the particular characteristic of interest, and otherwise may be associated with an entirely different characteristic of the sample **202**.

Referring now to FIG. **8**, illustrated is an alternative configuration of the optical computing device **700**, according to one or more embodiments. In FIG. **8**, a series of beam splitters **711***a*, **711***b*, **711***n* may be added to the first and second primary channels A**1**, A**2** and the reference channel A**3**, respectively, and used to separate or otherwise redirect the optically interacted radiation **206** As depicted, each beam splitter **711***a-n* may be configured to produce and direct a respective beam **712***a*, **712***b*, **712***n* of optically interacted radiation **206** toward a corresponding ICE **702***a-n*. Each ICE **702***a-n* may then be configured to transmit its respective modified electromagnetic radiation **706***a-n* toward a corresponding detector **704***a-n*, thereby generating the first, second, and additional output signals **508***a-n*, respectively. The first, second, and additional signals **508***a-n* may then be received by a signal processor **220** communicably coupled to each detector **704***a-n* and configured to computationally combine the first, second, and additional signals **508***a-n* in order to determine the characteristic of the sample **202**.

In some embodiments, the second detector **510** may again be used in the second or true reference channel B to detect electromagnetic radiating deviations exhibited by the electromagnetic radiation source **201**, and thereby normalize the signals **508***a-n* produced by the detectors **704***a-n*. The second detector **510** may be communicably coupled to the signal processor **220** such that the compensating signal **318** indicative of electromagnetic radiating deviations may be provided or otherwise conveyed thereto. The signal processor **220** may then be configured to computationally combine the compensating signal **318** with the signals **508***a-n*, and thereby normalize the signals **508***a-n* and provide a more accurate determination of the characteristic of the sample.

Referring now to FIG. **9**, illustrated is yet another alternative configuration of the optical computing device **700**, according to one or more embodiments. As illustrated in FIG. **9**, the optically interacted radiation **206** may be fed into or otherwise provided to, for example, an optical light pipe **714**. The optical light pipe **714** may be configured to convey the optically interacted radiation **206** individually to each of the first and second primary channels A**1**, A**2** and the reference channel A**3**. In some embodiments, the optical light pipe **714** may be a fiber optic bundle having a plurality of corresponding conveying bundles. In operation, a first bundle **714***a* may be configured to convey optically interacted radiation **206** to the first ICE **702***a* in the first primary channel A**1** in order to generate the modified electromagnetic radiation **706***a*; a second bundle **714***b* may be configured to convey optically interacted radiation **206** to the second ICE **702***b* in the second primary channel A**2** in order to generate the second optically interacted light **706***b*; and an additional bundle **714***n* may be configured to convey optically interacted radiation **206** to the additional ICE **702***n* in the reference channel A**3** in order to generate the additional modified electromagnetic radiation **706***n*. At least one additional bundle **714***x* may be configured to convey optically interacted radiation **206** to the second detector **510** in the second or true reference channel B in order to generate the compensating signal **318**. Processing of the resulting modified electromagnetic radiation **706***a-n* and signals **508***a-n* may be accomplished as generally described above.

It should be noted that the use of optical light pipes, such as the optical light pipe **714** discussed above, may be employed in any of the various embodiments and combinations discussed herein, without departing from the scope of the disclosure. Use of a light pipe, or a variation thereof, may prove advantageous in that the light pipe substantially removes interferent obstruction that may otherwise contaminate the optically interacted radiation **206** provided to the various ICEs.

Referring now to FIG. **10**, illustrated is another optical computing device **1000**, according to one or more embodiments. The device **1000** may be somewhat similar to the optical computing device **300** and **320** described with reference to FIGS. **3***a* and **3***b* and therefore the device **1000** may be best understood with reference thereto, where like numerals indicate like elements. The device **1000** may include a movable assembly **1002** having at least two ICEs associated therewith and various corresponding primary channels and at least one reference channel. As illustrated, the movable assembly **1002** may be characterized at least in one embodiment as a rotating disc **1003**, wherein the at least two ICEs are radially disposed for rotation therewith. Alternatively, the movable assembly **1002** may be characterized as a linear array **1005**, wherein the at least two ICEs are laterally offset from each other. FIG. **10** illustrates corresponding side and frontal views of both the rotating disc **1003** and the linear array **1005**, each of which is described in more detail below.

Those skilled in the art will readily recognize, however, that the movable assembly **1002** may be characterized as any type of movable assembly configured to sequentially align at least one detector with optically interacted light **206** and/or one or more ICE. For example, the movable assembly **1002** may include such apparatus or devices as, but not limited to, an oscillating or translating linear array of ICE, one or more scanners, one or more beam deflectors, combinations thereof, or the like. In other embodiments, the movable assembly **1002** may be characterized as an assembly including a plurality of optical light pipes (e.g., fiber optics) configured to perform optical beam splitting to a fixed array of ICE and/or detectors.

Varying embodiments of the rotating disc **1003** may include any number of ICE arranged about or near the periphery of the rotating disc **1003** and circumferentially-spaced from each other. In the illustrated embodiment, the rotating disc **1003** includes a first ICE **1004***a*, a second ICE **1004***b*, a third ICE **1004***c*, and a fourth ICE **1004***d*, but it will be appreciated that the rotating disc **1003** may also include any number of additional ICE **1004***n* as needed for the particular application. Each ICE **1004***a-n* may be similar in construction to the ICE **100** described above with reference to FIG. **1**, and configured to be either associated or disassociated with a particular characteristic of the sample **202**, such as is described above with reference to the first and second ICE **302**, **304** of FIG. **3***a*. In various embodiments, the rotating disc **1003** may be rotated at a frequency of about 0.1 RPM to about 30,000 RPM.

In operation, the rotating disc **1003** may rotate such that each individual ICE **1004***a-n* may be exposed to or otherwise optically interact with the optically interacted radiation **206** for a distinct brief period of time. In at least one embodiment, however, the movable assembly **1002** may be arranged antecedent to the sample **202** such that each ICE **1004***a-n* may be exposed to or otherwise optically interact with the electromagnetic radiation **204** for a brief period of time. Upon optically interacting with the optically interacted radiation **206** each ICE **1004***a-n* may be configured to produce modified electromagnetic radiation, for example, a first modified electromagnetic radiation **1006***a* emanating from the first ICE **1004***a*, a second modified electromagnetic radiation **1006***b* emanating from the second ICE **1004***b*, a third modified electromagnetic radiation **1006***c* emanating from the third ICE **1004***c*, a fourth modified electromagnetic radiation **1006***d* emanating from the fourth ICE **1004***d*, and an additional modified electromagnetic radiation **1006***n* emanating from the one or more additional ICE **1004***n*.

As each individual ICE **1004***a-n* aligns with the optically interacted light **206** to produce the modified electromagnetic radiations **1106***a-n*, respectively, corresponding first, second, third, and fourth primary channels A**1**, A**2**, A**3**, and A**4** and one or more reference channels Bn are thereby generated. Since the device **1000** is not necessarily limited to any specific number of ICE **1004***a-n*, a corresponding number of primary channels may also be defined by the device **1000** (e.g., primary channel(s) An). Moreover, it will be appreciated that, while the rotating disc **1003** may include any number of additional ICE **1004***n* as needed, any number of corresponding or otherwise unrelated reference channels B may also be included in the device **1000** (e.g., reference channels B**1**, B**2** . . . Bn), without departing from the scope of the disclosure. Whereas at least one of the one or more reference channels B would otherwise be configured to detect radiating deviations of the electromagnetic radiation source **201**, embodiments are contemplated herein where a spectrally active additional ICE **1004***n* is arranged within said reference channel B. As a result, the reference channel B may serve substantially the same purpose as the first, second, third, and fourth primary channels A**1**, A**2**, A**3**, A**4** by detecting and determining the characteristic of the sample **202**.

In one or more embodiments, however, at least one of the one or more reference channels B (e.g., B**1**, B**2**, . . . Bn) may include a neutral spectral element (not shown) configured to simply pass the optically interacted radiation **206** without optical-interaction. As a result, the neutral element may be configured to provide a neutral signal to the detector **212** that may be substantially similar to the compensating signal **318** as described above with reference to FIG. **3***a*, and thereby generate a true reference channel B, as generally described herein. In operation, the detector **212** may detect the neutral signal which may be indicative of radiating deviations stemming from the electromagnetic radiation source **201**.

Each beam of modified electromagnetic radiation **1006***a-n* may be detected by the detector **212** which may be configured to time multiplex the modified electromagnetic radiation **1006***a-n* between the individually-detected beams. For example, the first ICE **1004***a* may be configured to direct the first modified electromagnetic radiation **1006***a* toward the detector **212** at a first time T**1**, the second ICE **1004***b* may be configured to direct the second modified electromagnetic radiation **1006***b* toward the detector **212** at a second time T**2**, and so on until the one or more additional ICE **1004***n* may be configured to direct the additional modified electromagnetic radiation **1006** toward the detector **212** at an additional time Tn. Consequently, the detector **212** receives a plurality of distinct beams of modified electromagnetic radiation **1006***a-n* which may be computationally combined by the detector **212** in order to provide an output in the form of a voltage that corresponds to the characteristic of the sample. In some embodiments, these beams of modified electromagnetic radiation **1006***a-n* may be averaged over an appropriate time domain (e.g., about 1 millisecond to about 1 hour) to more accurately determine the characteristic of the sample **202**.

The time multiplexed computation from the various primary channels A**1**, A**2**, . . . An and reference channel(s) B (e.g., B**1**, B**2**, . . . Bn) may involve a variety of mathematical relationships, including, for example, a linear relationship, a polynomial function, an exponential function, and or a logarithmic function, or a combination thereof. In these cases, a variety of normalization mathematics between the primary channels A**1**, A**2**, . . . An and reference channel(s) B may be applied. For example, the signals A**1**, A**2**, . . . An may each be normalized by dividing them each by B**1**, B**2**, . . . Bn (or a mathematical combination of B**1**, B**2**, . . . Bn) to achieve, for example, A**1**/B, A**2**/B . . . An/B, before the mathematical relationship between A**1**/B and A**2**/B is applied. In other cases, the mathematical relationship between A**1**, A**2**, . . . An may be applied, with the resultant normalized by B**1**, B**2** . . . Bn (or a mathematical combination of B**1**, B**2** . . . Bn). In even other cases, a combination of these two normalization methods may be applied. Those skilled in the art will be familiar with both general methods, and can choose which method is most applicable given the specific relationships involved. In one embodiment, for example, the compensating signal B**1**, B**2** . . . Bn and the output signals A**1**, A**2** . . . An are combined using principal component analysis techniques such as, but not limited to, standard partial least squares which are available in most statistical analysis software packages (e.g., XL Stat for MICROSOFT® EXCEL®; the UNSCRAMBLER® from CAMO Software and MATLAB® from MATHWORKS®). Finally, it is understood by those skilled in the art that fractions or multiples of the quantity B may be employed, as well as multiplication of the quantity (1/B).

As will be appreciated, each of the ICE **1004***a-n* may be specially-designed to detect or otherwise configured to be associated with the particular characteristic of interest. In other embodiments, however, one or more of the ICE **1004***a-n* may be configured to be disassociated with the particular characteristic of interest, and otherwise may be associated with an entirely different characteristic of the sample **202**. In yet other embodiments, each of the one or more ICE **1004***a-n* may be configured to be disassociated with the particular characteristic of interest, and otherwise may be associated with an entirely different characteristic of the sample **202**. Advantages of this approach can include the ability to analyze multiple analytes in multiple respective channels using a single optical computing device and the opportunity to assay additional analytes simply by adding additional ICEs to the rotating disc **1003**.

The linear array **1005** may also include the first, second, third, and fourth ICE **1004***a-d* and the one or more additional ICE **1004***n*, although aligned linearly as opposed to radially positioned. The linear array **1005** may be configured to oscillate or otherwise translate laterally or vertically such that each ICE **1004***a-n* is exposed to or otherwise able to optically interact with the optically interacted radiation **206** for a distinct brief period of time. Similar to the rotating disc **1003**, the linear array **1005** may be configured to produce modified electromagnetic radiation **1006***a-n*. Again, as each individual ICE **1004***a-n* aligns with the optically interacted light **206** to produce the modified electromagnetic radiations **1106***a-n*, respectively, corresponding first, second, third, and fourth primary channels A**1**, A**2**, A**3**, and A**4** and one or more reference channels B (e.g., B**1**, B**2**, . . . Bn) are thereby generated. As will be appreciated, any number of ICE **1004***a-n* may be arranged on the linear array **1005** in order to determine the characteristic of the sample **202**, and therefore any number of corresponding primary channels A**1**-A**4** and additional reference channels B may also be generated.

Moreover, as with the rotating disc **1003** embodiment, the detector **212** may be configured to time multiplex the modified electromagnetic radiation **1006***a-n* between the individually-detected beams and subsequently provide an output in the form of a voltage that corresponds to the characteristic of the sample **202**. Even further, at least one of the ICE **1004***a-n* may be a neutral element configured to provide a neutral signal to the detector **212** in a true reference channel B that may be computationally combined with the remaining beams of modified electromagnetic radiation **1006***a-n* to compensate for electromagnetic radiating deviations stemming from the electromagnetic radiation source **201**.

Referring now to FIG. **11**, with continued reference to FIG. **10**, illustrated is another exemplary optical computing device **1100**, according to one or more embodiments. The device **1100** may be somewhat similar to the device **1000** of FIG. **10**, and therefore may be best understood with reference thereto where like numerals indicate like elements. The device **1100** may include a movable assembly **1102** similar in some respects to the movable assembly **1002** of FIG. **10**. For example, FIG. **11** illustrates an alternative embodiment of a rotating disc **1103**. The rotating disc **1103** in FIG. **11**, however, may include multiple radially-offset rows or arrays of ICE, such as a first radial array **1104***a*, a second radial array **1104***b*, and one or more additional radial arrays **1104***n*. Accordingly, while three radial arrays **1104***a*, **1104***b*, and **1104***n* are shown in FIG. **11**, it will be appreciated that the rotating disc **1103** may include more or less than three arrays **1104***a-n*, without departing from the scope of the disclosure.

Each radially-offset radial array **1104***a-n* may include a plurality of ICE **1106** circumferentially-spaced from each other. Again, while a particular number of ICE **1106** are specifically depicted in FIG. **11**, it should be appreciated that any number of ICE **1106** may be used in the rotating disc **1103**, without departing from the scope of the disclosure. Each ICE **1106** may be similar in construction to the ICE **100** described above with reference to FIG. **1**, and configured to be either associated or disassociated with a particular characteristic of the sample **202**, such as is described above with reference to the first and second ICE **302**, **304** of FIG. **3***a*. In operation, the rotating disc **1103** rotates such that the one or more ICE **1106** may each be exposed to or otherwise optically interact with the optically interacted radiation **206** for a distinct brief period of time. In at least one embodiment, however, the rotating disc **1103** may be arranged antecedent to the sample **202**, and therefore the one or more ICE **1106** may be exposed to or otherwise optically interact with the electromagnetic radiation **204** for a brief period of time. Upon optically interacting with the optically interacted radiation **206**, each ICE **1106** may be configured to produce an individual or combined beam of modified electromagnetic radiation **1008** directed toward the detector **212**. Moreover, as each individual ICE **1106** aligns with the optically interacted light **206** to produce corresponding modified electromagnetic radiations **1008**, several distinct primary channels for conveying and detecting light are generated, and at least one reference channel is generated that may operate substantially similarly to a primary channel since an ICE **1106** is arranged therein as opposed to a traditional neutral element.

Each individual or combined beam of modified electromagnetic radiation **1008** may be detected by the detector **212** which may be configured to time multiplex the modified electromagnetic radiation **1008** between the combined or individually-detected beams in each primary and reference channel. Consequently, the detector **212** receives a plurality of beams of modified electromagnetic radiation **1008** which may be computationally combined by the detector **212** in order to provide an output in the form of a voltage that corresponds to the characteristic of the sample. Moreover, one or more of the ICE **1106** may be a neutral element or otherwise an aperture may be defined in the rotating disc **1103** and configured to provide a neutral signal to the detector **212**, and thereby provide a true reference channel, as generally described above with reference to FIG. **10**. The neutral signal may be indicative of radiating deviations stemming from the electromagnetic radiation source **201**, and the detector **212** may be configured to computationally combine the neutral signal with the remaining beams of modified electromagnetic radiation **1008** to compensate for electromagnetic radiating deviations stemming from the electromagnetic radiation source **201**, and thereby provide a more accurate determination of the characteristic of the sample.

While the various embodiments disclosed herein provide that the electromagnetic radiation source **201** is used to provide electromagnetic radiation that optically interacts with the at least two ICEs, those skilled in the art will readily recognize that electromagnetic radiation may be derived from the sample **202** itself, and otherwise derived independent of the electromagnetic radiation source **201**. For example, various substances naturally radiate electromagnetic radiation that is able to optically interact with the at least two ICEs. In some embodiments, the sample **202** may be a blackbody radiating substance configured to radiate heat that may optically interact with the at least two ICEs. In other embodiments, the sample **202** may be radioactive or chemo-luminescent and therefore radiate electromagnetic radiation that is able to optically interact with the at least two ICEs. In yet other embodiments, the electromagnetic radiation may be induced from the sample **202** by being acted upon mechanically, magnetically, electrically, combinations thereof, or the like. For instance, in at least one embodiment a voltage may be placed across the sample **202** in order to induce the electromagnetic radiation. As a result, embodiments are contemplated herein where the electromagnetic radiation source **201** is entirely omitted from the particular optical computing device.

Therefore, the present invention is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed above are illustrative only, as the present invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered, combined, or modified and all such variations are considered within the scope and spirit of the present invention. While compositions and methods are described in terms of "comprising," "containing," or "including" various components or steps, the compositions and methods can also "consist essentially of" or "consist of" the various components and steps. All numbers and ranges disclosed above may vary by some amount. Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range is specifically disclosed. In particular, every range of values (of the form, "from about a to about b," or, equivalently, "from approximately a to b," or, equivalently, "from approximately a-b") disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. Moreover, the indefinite articles "a" or "an," as used in the claims, are defined herein to mean one or more than one of the element that it introduces.

What is claimed is:

1. A method of determining a desired characteristic of a sample, comprising:

optically interacting electromagnetic radiation with the sample and a first integrated computational element arranged within a primary channel;

optically interacting the electromagnetic radiation with the sample and a second integrated computational element arranged within a reference channel, wherein the first integrated computational element is selected according to a spectral response associated or disassociated with the desired characteristic of the sample, and the second integrated computational element is selected according to a spectral response associated or disassociated with the desired characteristic of the sample, wherein the spectral response disassociated with the desired characteristic of the sample is a regression vector associated with a second characteristic of the sample different from the desired characteristic of the sample;

producing first and second modified electromagnetic radiations from the first and second integrated computational elements, respectively;

receiving the first modified electromagnetic radiation with a first detector, and receiving the second modified electromagnetic radiation with a second detector;

generating a first output signal with the first detector and a second output signal with the second detector; and

computationally combining the first and second output signals with a signal processor to determine the desired characteristic of the sample.

2. The method of claim **1**, wherein optically interacting the electromagnetic radiation with the sample and the first and second integrated computational elements comprises transmitting the electromagnetic radiation through at least one of the first and second integrated computational elements.

3. The method of claim **1**, wherein optically interacting the electromagnetic radiation with the sample and the first and second integrated computational elements comprises reflecting the electromagnetic radiation off of at least one of the first and second integrated computational elements.

4. The method of claim **1**, further comprising:

producing a first beam of light directed toward the first integrated computational element with a beam splitter; and

producing a second beam of light directed toward the second integrated computational element with the beam splitter.

5. The method of claim **1**, further comprising:

detecting electromagnetic radiation with a third detector arranged within a second reference channel;

generating a compensating signal with the second detector, the compensating signal being indicative of electromagnetic radiating deviations;

receiving the compensating signal with the signal processor; and

computationally combining the compensating signal with the first and second output signals to normalize the first and second output signals.

6. The method of claim **5**, further comprising reflecting a portion of the electromagnetic radiation toward the third detector with a beam splitter.

7. The method of claim **5**, further comprising directly receiving the electromagnetic radiation with the third detector.

8. The method of claim **5**, wherein computationally combining the compensating signal with the first and second output signals comprises implementing a mathematical relationship selected from the group consisting of a linear relationship, a polynomial function, an exponential function, a logarithmic function, and any combination thereof.

9. The method of claim **1**, further comprising emitting the electromagnetic radiation with an electromagnetic radiation source selected from the group consisting of a light bulb, light emitting device, laser, blackbody, photonic crystal, and an X-Ray source.

10. A method, comprising:

emitting electromagnetic radiation from an electromagnetic radiation source;

optically interacting the electromagnetic radiation with a sample and thereby generating optically interacted radiation;

optically interacting the optically interacted radiation with a first integrated computational element arranged within a first primary channel and thereby generating a first modified electromagnetic radiation;

reflecting a portion of the optically interacted radiation off the first integrated computational element;

optically interacting the portion of the optically interacted radiation with a second integrated computational element arranged within a second primary channel and thereby generating a second modified electromagnetic radiation, wherein the first integrated computational element is selected according to a spectral response associated or disassociated with a desired characteristic of the sample, and the second integrated computational element is selected according to a spectral response associated or disassociated with the desired characteristic of the sample, wherein the spectral response disassociated with the desired characteristic of the sample is a regression vector associated with a second characteristic of the sample different from the desired characteristic of the sample;

receiving the first and second modified electromagnetic radiations with corresponding first and second detectors, respectively;

generating a first output signal with the first detector and a second output signal with the second detector; and

computationally combining the first and second output signals with a signal processor to determine the desired characteristic of the sample.

11. The method of claim 10, further comprising:
detecting electromagnetic radiation with a third detector arranged within a reference channel;
generating a compensating signal with the second detector, the compensating signal being indicative of electromagnetic radiating deviations;
receiving the compensating signal with the signal processor; and
computationally combining the compensating signal with the first and second output signals to normalize the first and second output signals.

12. The method of claim 11, further comprising reflecting a portion of the electromagnetic radiation toward the third detector with at least one of the first and second integrated computational elements.

13. The method of claim 11, further comprising receiving a portion of the electromagnetic radiation with the third detector as transmitted through at least one of the first and second integrated computational elements.

14. The method of claim 11, further comprising directly receiving the electromagnetic radiation with the third detector.

15. The method of claim 10, wherein emitting the electromagnetic radiation from the electromagnetic radiation source comprises emitting the electromagnetic radiation from a source selected from the group consisting of a light bulb, light emitting device, laser, blackbody, photonic crystal, and an X-Ray source.

16. A method, comprising:
emitting electromagnetic radiation from an electromagnetic radiation source;
optically interacting the electromagnetic radiation with a sample and thereby generating optically interacted radiation;
splitting the optically interacted radiation with a first beam splitter into first and second beams of optically interacted radiation;
optically interacting the first beam of optically interacted radiation with a first integrated computational element arranged within a first primary channel and thereby generating a first modified electromagnetic radiation;
splitting the second beam of optically interacted radiation with a second beam splitter into third and fourth beams of optically interacted radiation;
optically interacting the third beam of optically interacted radiation with a second integrated computational element arranged within a second primary channel and thereby generating a second modified electromagnetic radiation, wherein the first integrated computational element is selected according to a spectral response associated or disassociated with the characteristic of the sample, and the second integrated computational element is selected according to a spectral response associated or disassociated with the same characteristic of the sample;
receiving the first and second modified electromagnetic radiations with corresponding first and second detectors, respectively;
generating a first output signal with the first detector and a second output signal with the second detector; and
computationally combining the first and second output signals with a signal processor to determine the characteristic of interest of the sample.

17. The method of claim 16, further comprising:
detecting electromagnetic radiation with a third detector arranged within a reference channel;
generating a compensating signal with the second detector, the compensating signal being indicative of electromagnetic radiating deviations;
receiving the compensating signal with the signal processor; and
computationally combining the compensating signal with the first and second output signals to normalize the first and second output signals.

18. The method of claim 17, wherein detecting the electromagnetic radiation with the third detector comprises receiving at least a portion of the fourth beam of optically interacted radiation with the third detector.

19. The method of claim 18, further comprising receiving a portion of the fourth beam of optically interacted radiation with the third detector with the third detector as transmitted through at least one of the first and second integrated computational elements.

20. The method of claim 10, wherein emitting the electromagnetic radiation from the electromagnetic radiation source comprises emitting the electromagnetic radiation from a source selected from the group consisting of a light bulb, light emitting device, laser, blackbody, photonic crystal, and an X-Ray source.

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